SAND2016-4276C

Sandia National Laboratories

8 – 12 May 2016

Conceptual designs of four next-generation pulsed-power accelerators for high-energy-density-physics experiments

ICMRE 2016: The First International Conference on Matter and Radiation at Extremes (Chengdu, China)

Sandia National Laboratories

A large collaboration has developed the conceptual designs.

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Outline

- Pulsed-power technology
- Present state of the art of pulsed power: the Z accelerator
- Proposed architecture for the designs of next-generation machines
- Proposed requirements for machines optimized for material-physics research
- Thor: a megabar-class accelerator
- Neptune: a 10-megabar-class accelerator
- Proposed requirements for machines optimized for fusion experiments
- Z 300: a thermonuclear-ignition accelerator
- Z 800: a high-yield-fusion accelerator
- Linear transformer drivers (LTDs): the prime power source of Z 300 and Z 800
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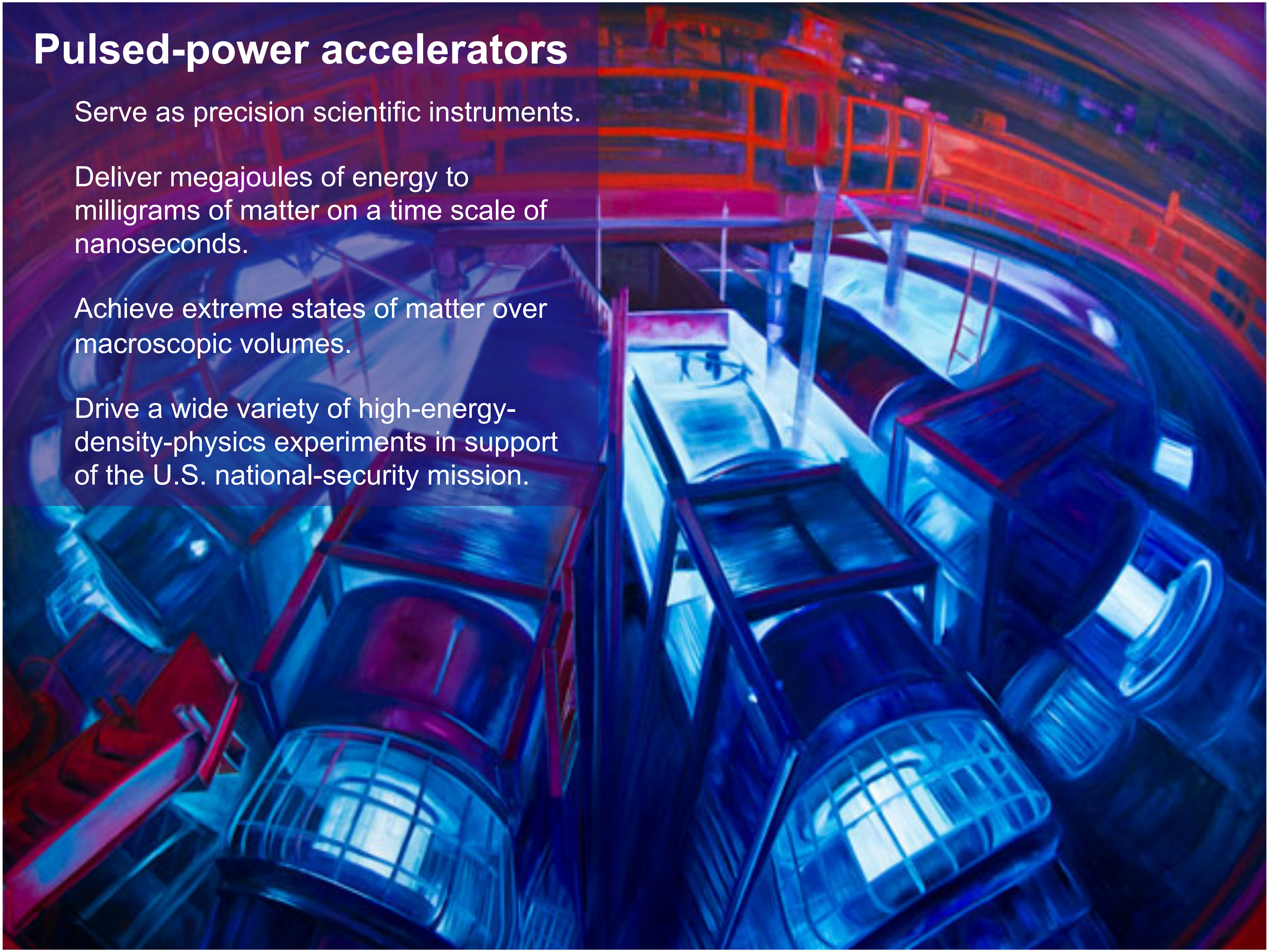
Pulsed-power accelerators

Serve as precision scientific instruments.

Deliver megajoules of energy to milligrams of matter on a time scale of nanoseconds.

Achieve extreme states of matter over macroscopic volumes.

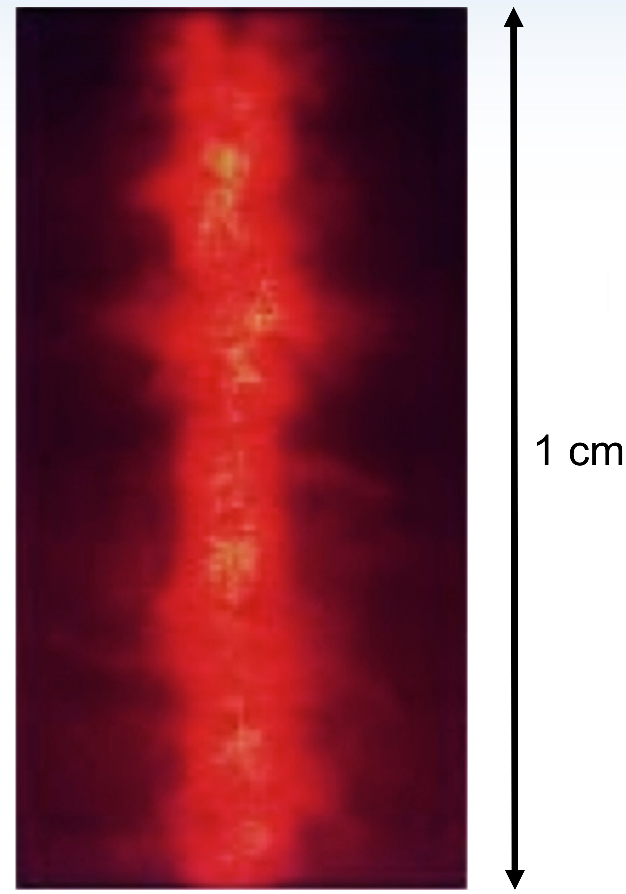
Drive a wide variety of high-energy-density-physics experiments in support of the U.S. national-security mission.



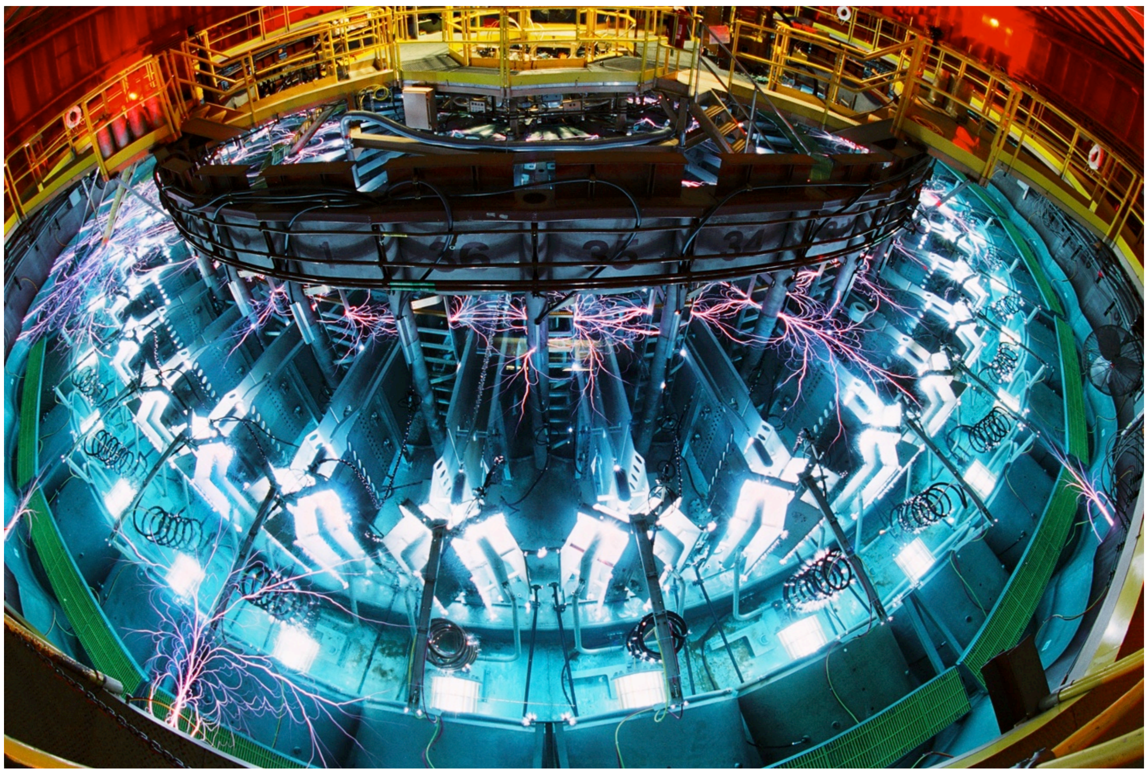
Pulsed-power experiments presently deliver the following:

- Kinetic energy per atom: 1 MeV.
- Implosion velocities: 100 cm/μs.
- Shock velocities: 30 km/s.
- Temperatures: 5 keV.
- Magnetic pressures: 5 Mbar.
- Energy radiated in K-shell x rays: 400 kJ.
- Energy radiated in thermal x rays: 2.3 MJ.
- Power radiated in thermal x rays: 330 TW.

100-ps x-ray image of a 280-TW z pinch at stagnation



(Deeney, Douglas, Spielman, and colleagues, PRL, 1998.)



20-TW 33-m-diameter Saturn accelerator

(Bloomquist, Corcoran, Spielman, and colleagues.)

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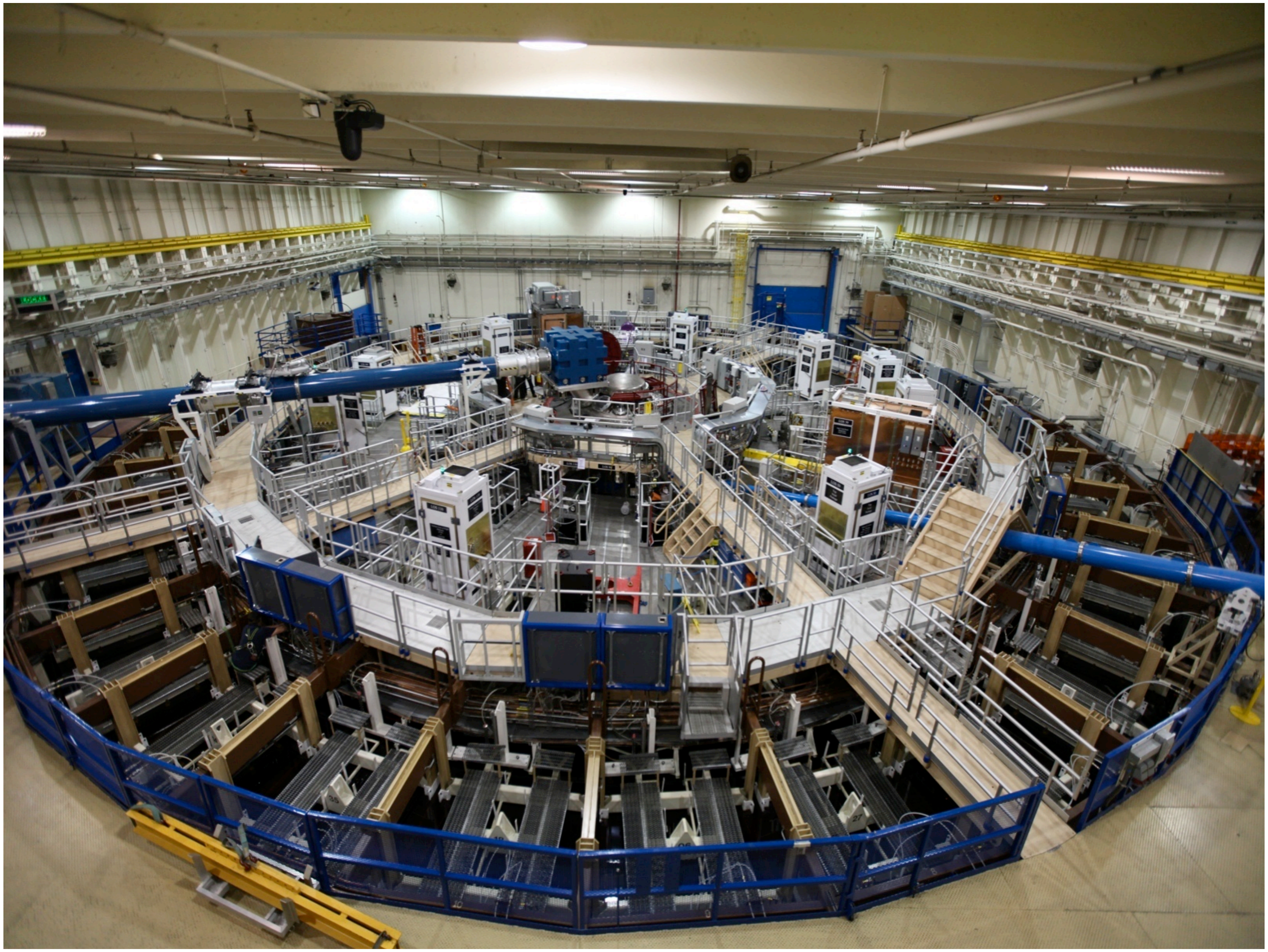
Sandia's Z accelerator is presently the world's largest and most powerful pulsed-power machine.

E_{stored} = 20 MJ V_{stack} = 4 MV I_{load} = 26 MA $E_{radiated}$ = 2.3 MJ

$P_{electrical}$ = 85 TW L_{vacuum} = 12 nH $\tau_{implosion}$ = 130 ns   diameter = 33 m

- Since 1997 we have conducted, on average, 160 Z shots each year.
- To date, we have conducted 3000 shots altogether.
- Z shots drive a wide variety of experiments in support of the U.S. national-security mission.

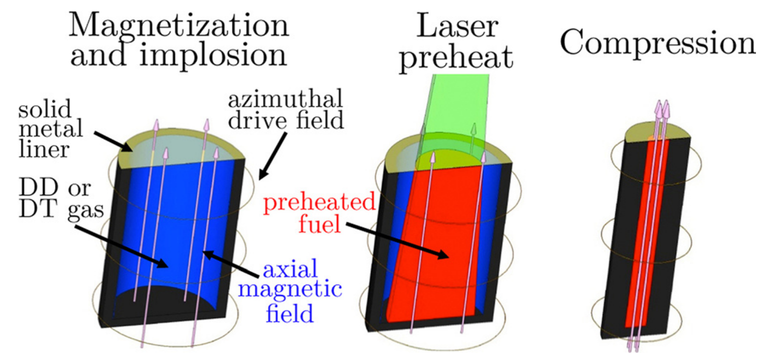


Results of experiments conducted on Z have motivated ~1000 peer-reviewed journal articles.

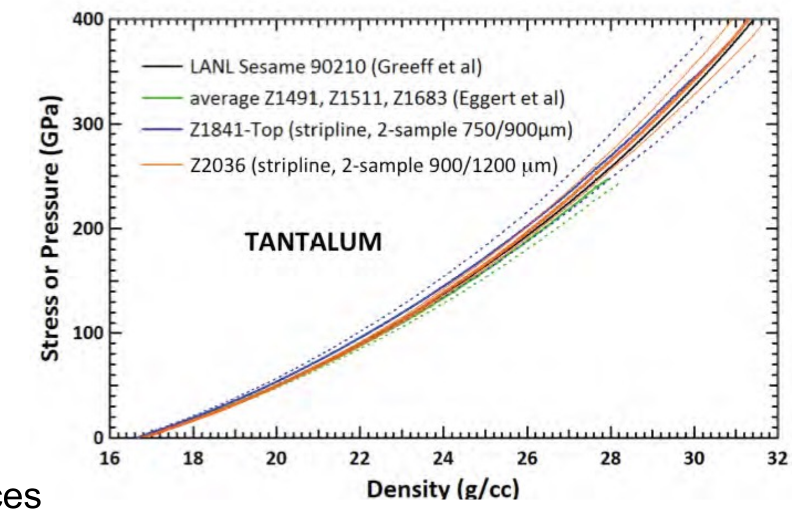
Research areas advanced by the experiments include the following:

- Inertial confinement fusion (ICF).
- Material physics.
- Plasma physics.
- Radiation physics.
- Laboratory astrophysics.
- Accelerator physics.

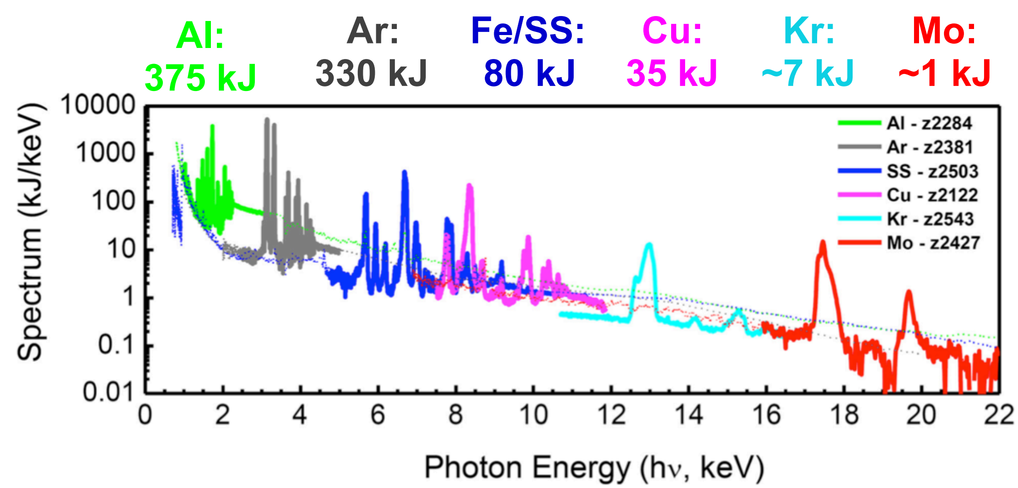
magnetized liner inertial fusion (MagLIF) concept



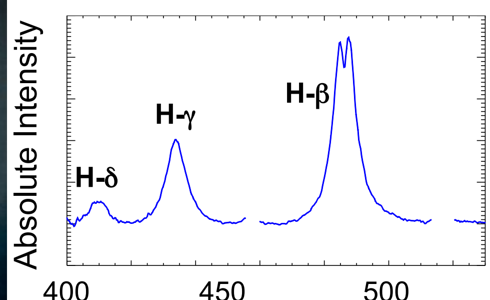
quasi-isentrope of tantalum to 4 Mbar



K-shell x-ray sources



white-dwarf line shapes



Z's success naturally leads to the question: How do we advance to the next technological level?

How do we design next-generation pulsed-power accelerators?

How do we increase *substantially* the power and energy delivered to the load, to allow high-energy-density-physics (HEDP) experiments to be conducted over heretofore inaccessible parameter regimes?

How do we achieve thermonuclear ignition and high-yield fusion?

At the same time, how do we make the accelerators safe, robust, and reliable?

In other words:

How do we design accelerators that will serve as a suitable legacy from us to the next generation of HEDP scientists?

This presentation will address this question.

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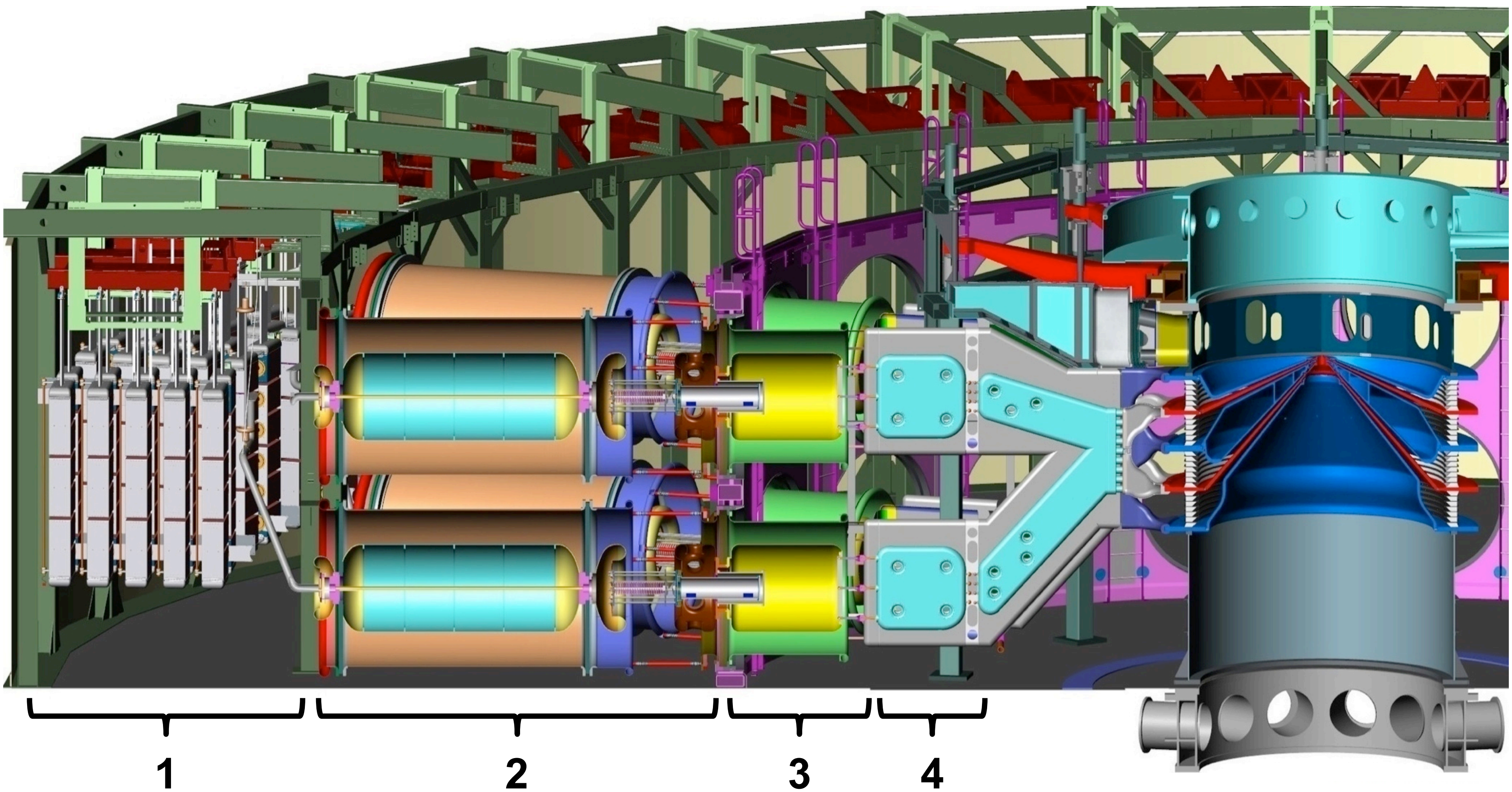
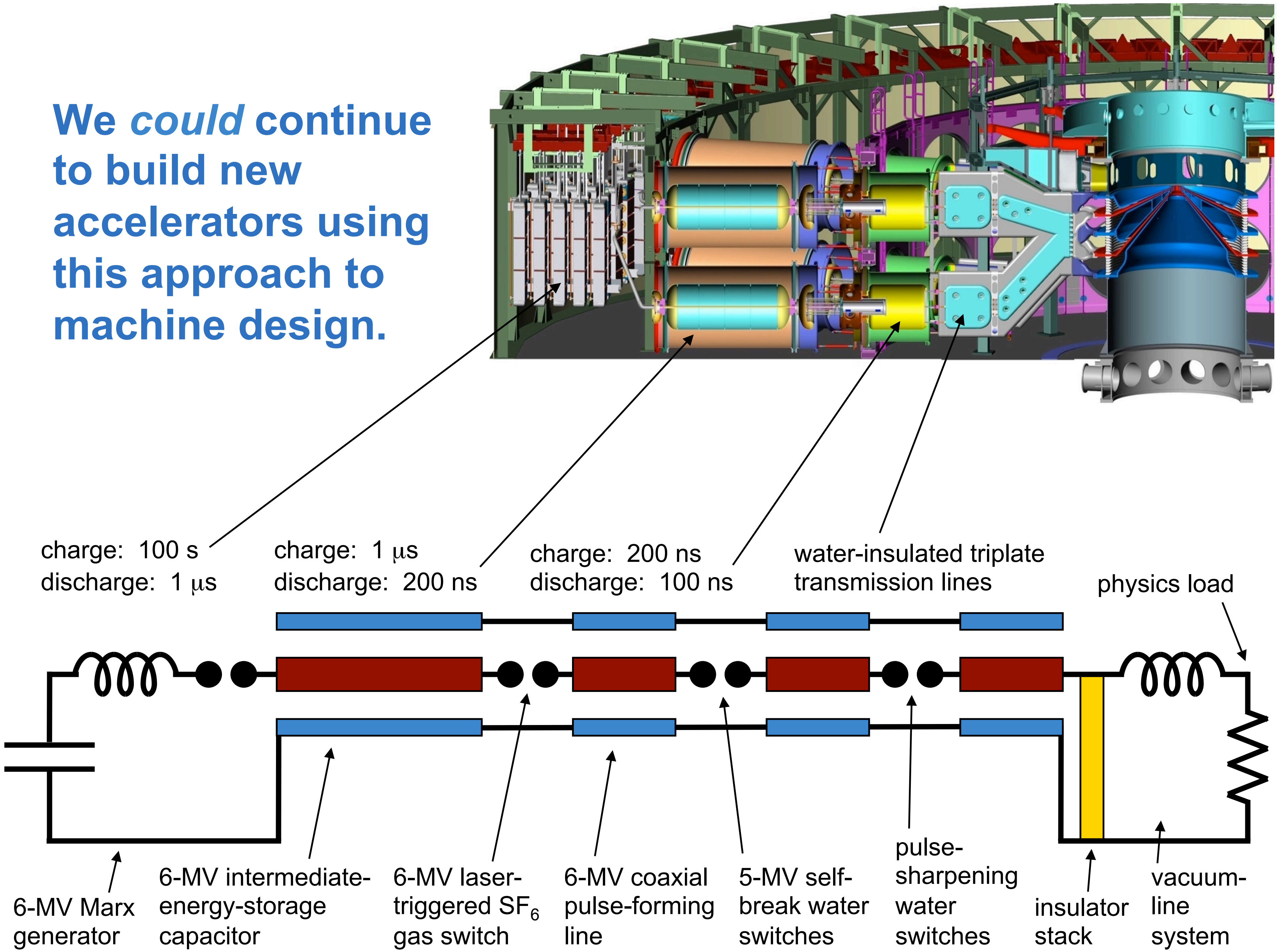
For decades, the HEDP community has designed machines with an architecture similar to that of Z.

- Each of Z's 36 modules includes four stages of electrical-pulse compression.
- These introduce impedance mismatches, which create reflections of the power pulse.
- The reflections damage hardware, reduce efficiency, and complicate efforts to model a Z shot.



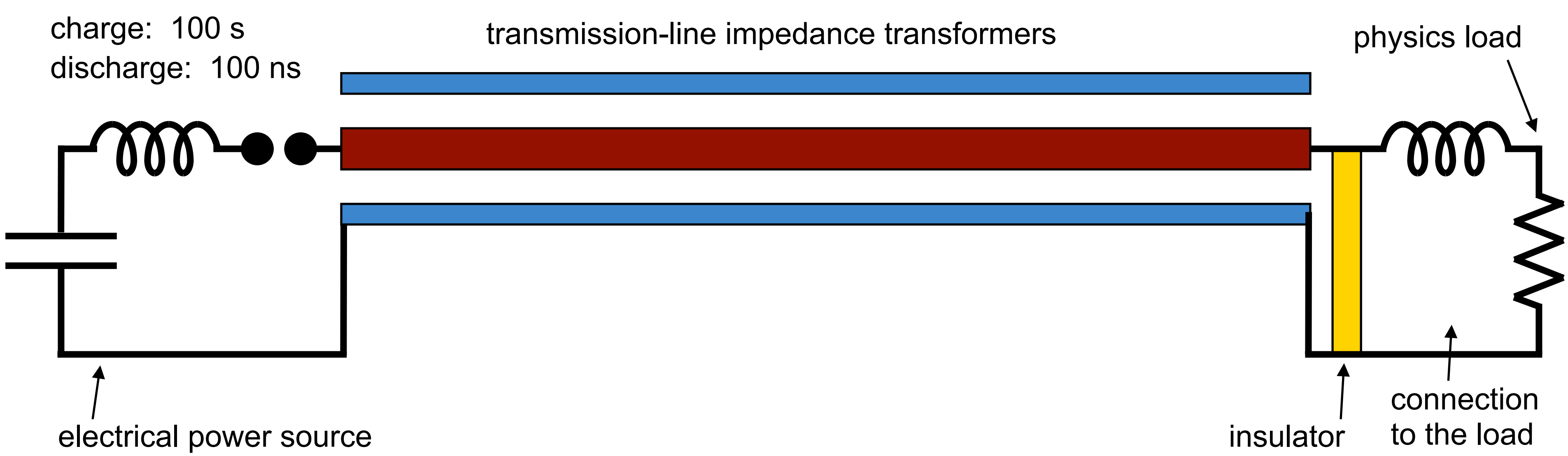
We *could* continue to build new accelerators using this approach to machine design.



We propose *instead* to base the designs of next-generation accelerators on a new architecture.

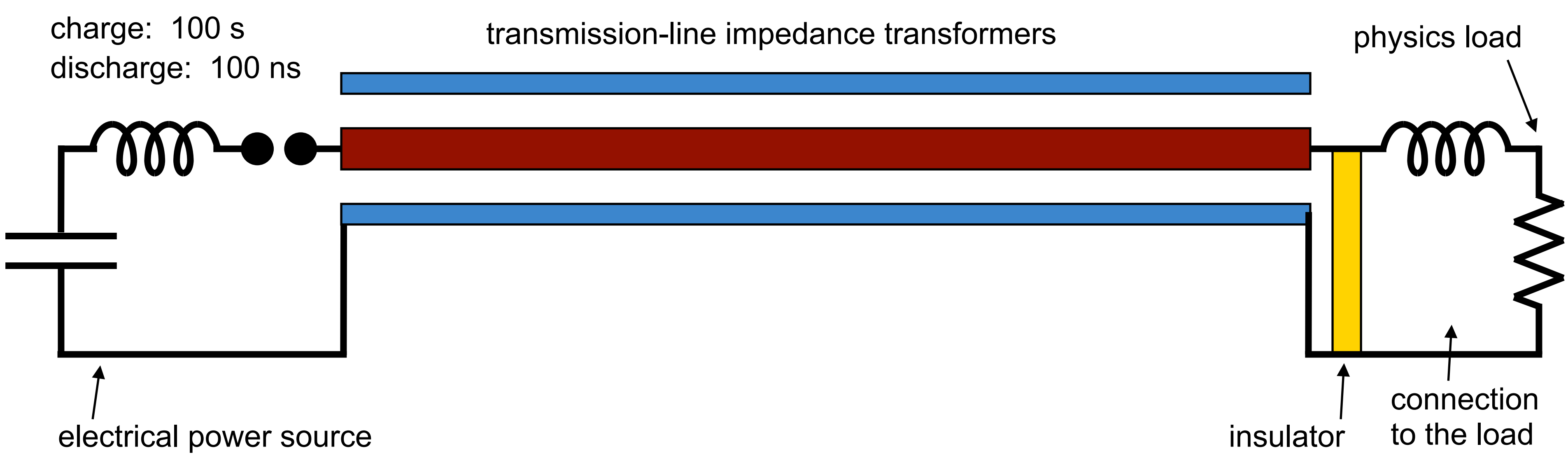
The architecture is based on two concepts: single-stage electrical-pulse compression and impedance matching.

- We propose to go from DC-charged capacitors to the requisite 100-ns pulse in a single step.
  - This eliminates the need for pulse-compression hardware.
  - This in turn simplifies machine design, increases efficiency, increases component lifetimes, and facilitates simulations of an accelerator shot.
- We propose to use impedance matching throughout.
  - Impedance matching reduces reflections of the power pulse within the accelerator, and improves accelerator efficiency.



Let us consider how the new architecture might be applied to the designs of next-generation accelerators.

We begin by considering accelerators optimized for material-physics experiments.



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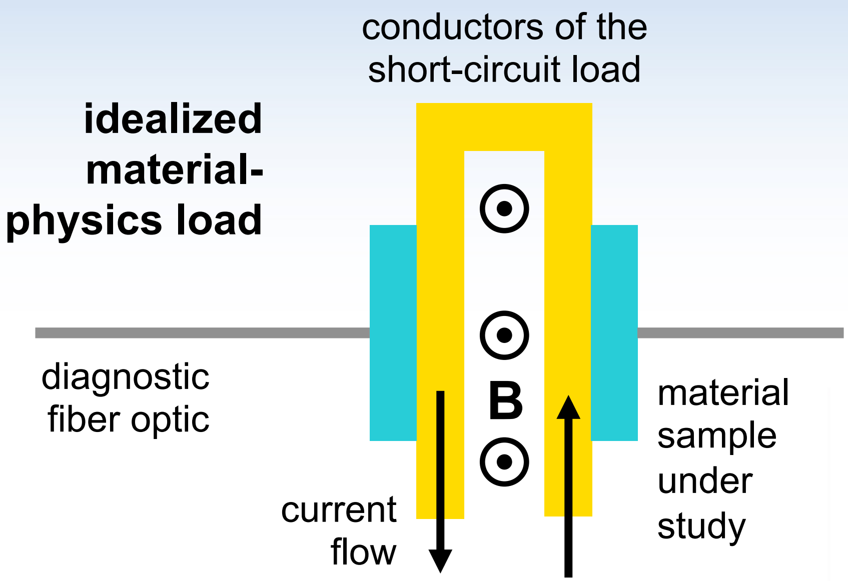
Z and other pulsed-power machines are used to drive material-physics experiments.

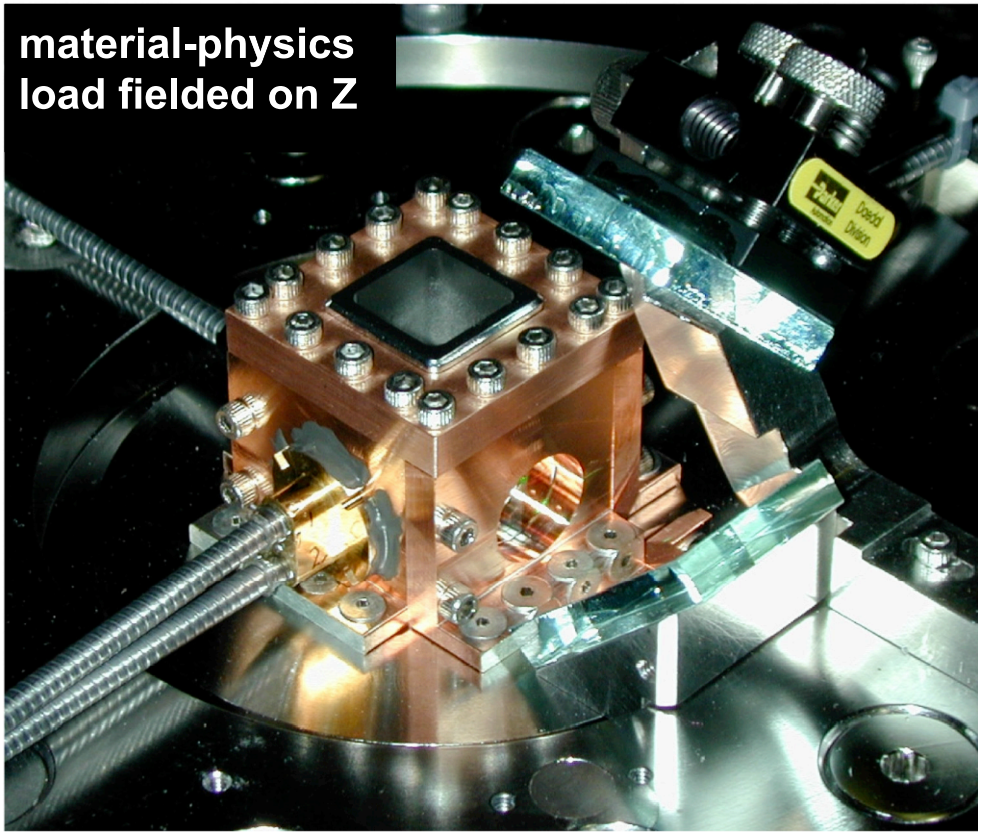
- This application is outlined in seminal publications by Reisman and colleagues (JAP, 2001) and Hall and co-workers (RSI, 2001).
- The magnetic pressure generated within a short-circuit load drives the experiment.

$$P_{magnetic} = \frac{\mu_0 I^2}{2 w^2}$$

I = current

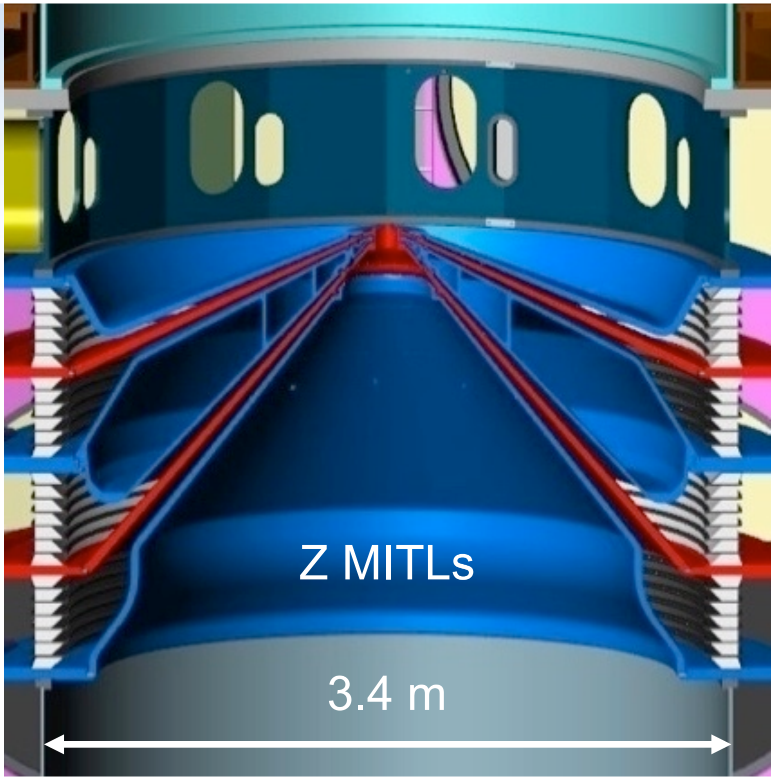
w = width of the conductor

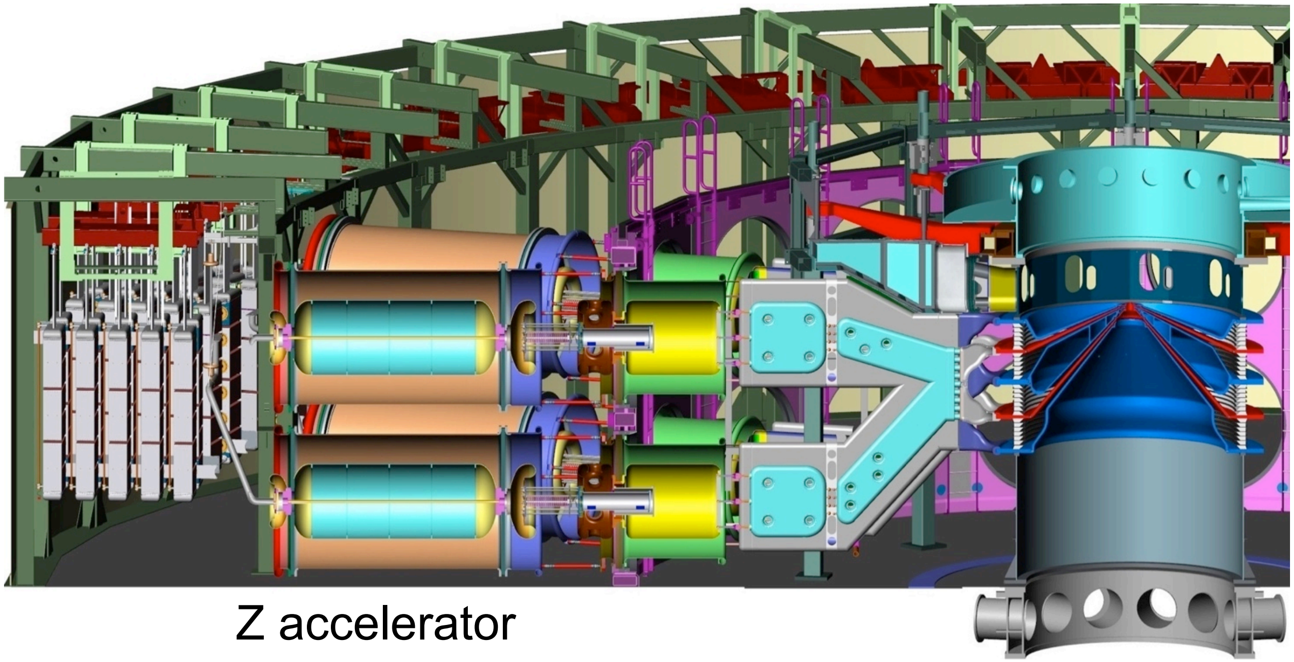




There is a need for accelerators that are *optimized* for material-physics experiments.

- Z was optimized to deliver a 26-MA 100-ns current pulse to an imploding z-pinch load.
  - Such experiments generate a high voltage, which requires use of a 3.4-m-diameter stack-MITL system.
- A material-physics experiment requires a ~1000-ns current pulse, which generates much lower voltages.
  - A 3.4-m stack-MITL system is unnecessary for such experiments, and reduces system efficiency.
- Hazardous-material experiments are conducted on Z within a containment system.
  - The containment system is open at t = 0, and is explosively closed.
  - It would be safer to use a *passive* containment system, one that is *always closed*.

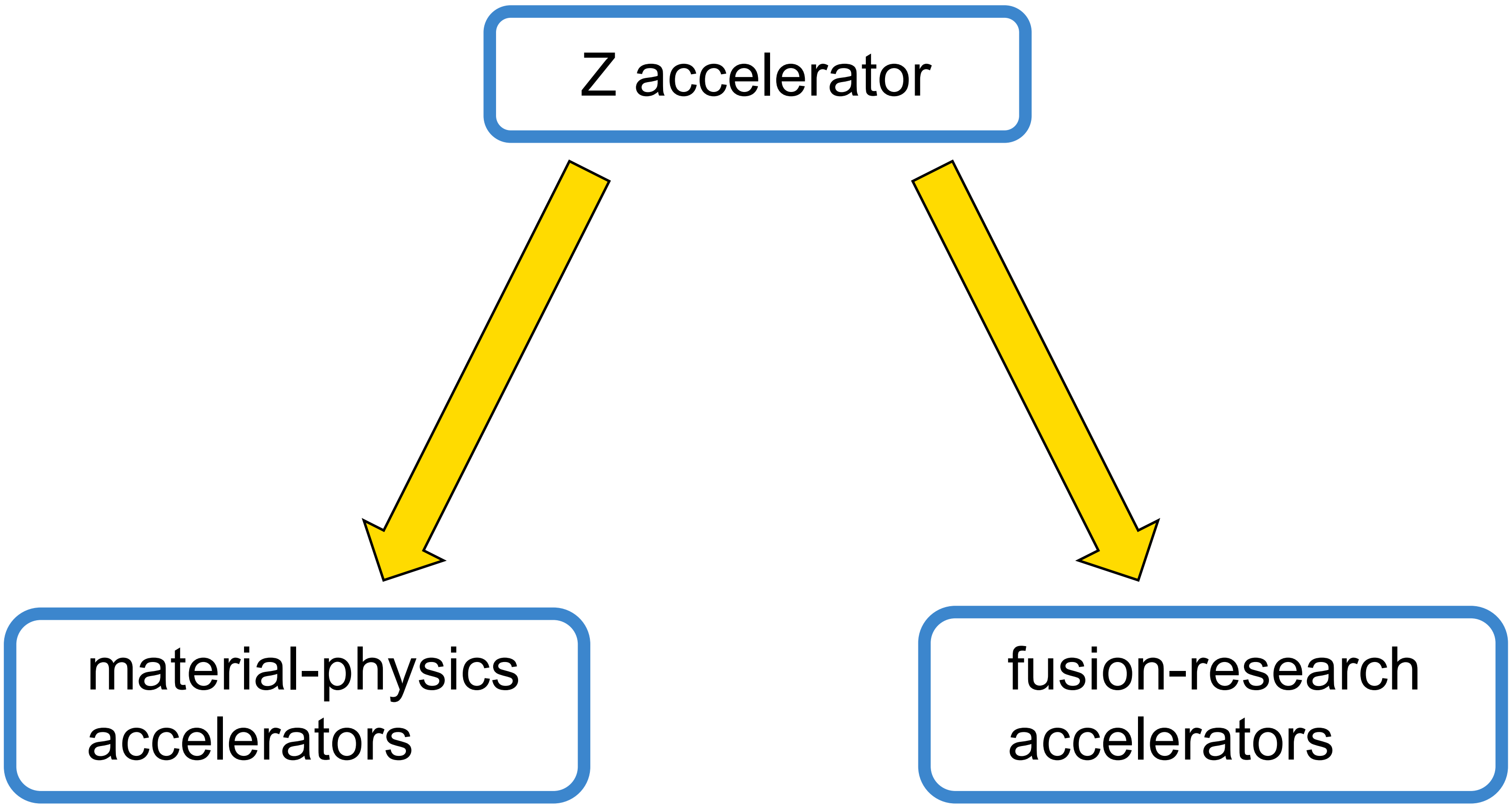




Z accelerator

Instead of building *one* next-generation machine that tries to do everything, we propose to develop *two* classes of machines.

- One class will be optimized for material-physics experiments.
- The other, thermonuclear-fusion research.
- We are proposing a branch in the evolution of megampere-class accelerators.



We propose the following requirements for machines that are optimized for material-physics research.

- Pulse compression: From DC-charged capacitors to the requisite pulse in a single step.
- Impedance profile: Impedance matched throughout.
- Magnetic pressures: At least one megabar.
- Containment system: Passive, one that is closed at t = 0 and does not use explosives.
- Size of the primary containment system: Less than ~1 m in diameter.
- Pulse shaping: The accelerators should be arbitrary waveform generators.
    - The machines should be designed to generate an arbitrary current-pulse shape at the load, and achieve a target shape with an accuracy better than 1%.
- Accelerator simulations: The accelerator designs should enable fast and accurate circuit simulations of a shot.
- Accelerator lifetime: The accelerators should use robust long-lifetime components.
- Engineered safety: The accelerators should not use potentially lethal energy-storage capacitors, SF_6 or any other asphyxiant or greenhouse gas, high-power lasers, or materials that include lead or other neurotoxins.

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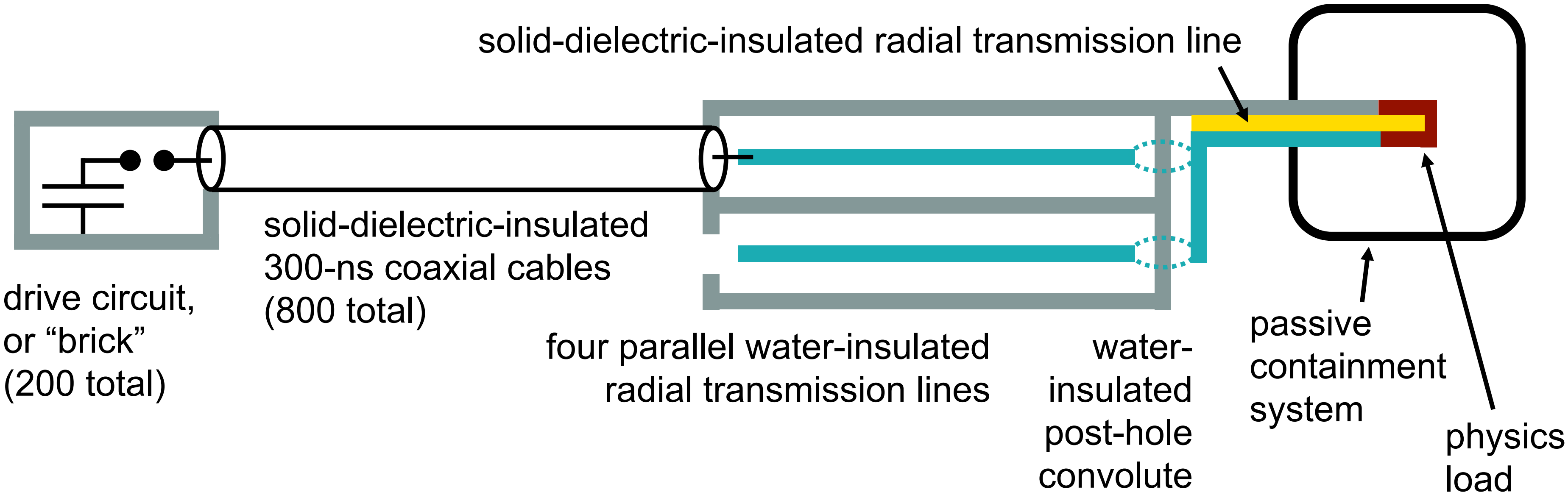
We have developed a conceptual design of Thor.

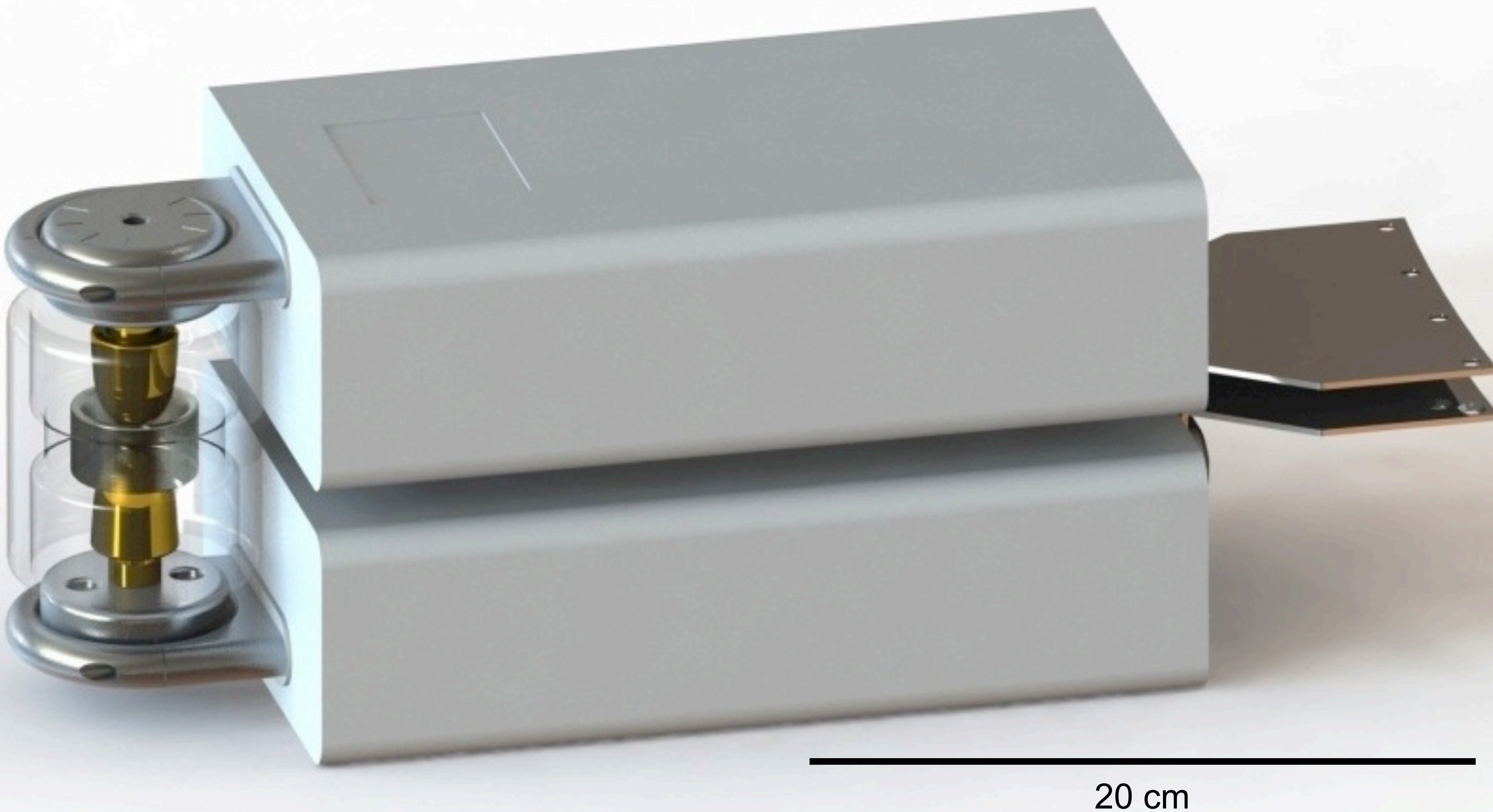


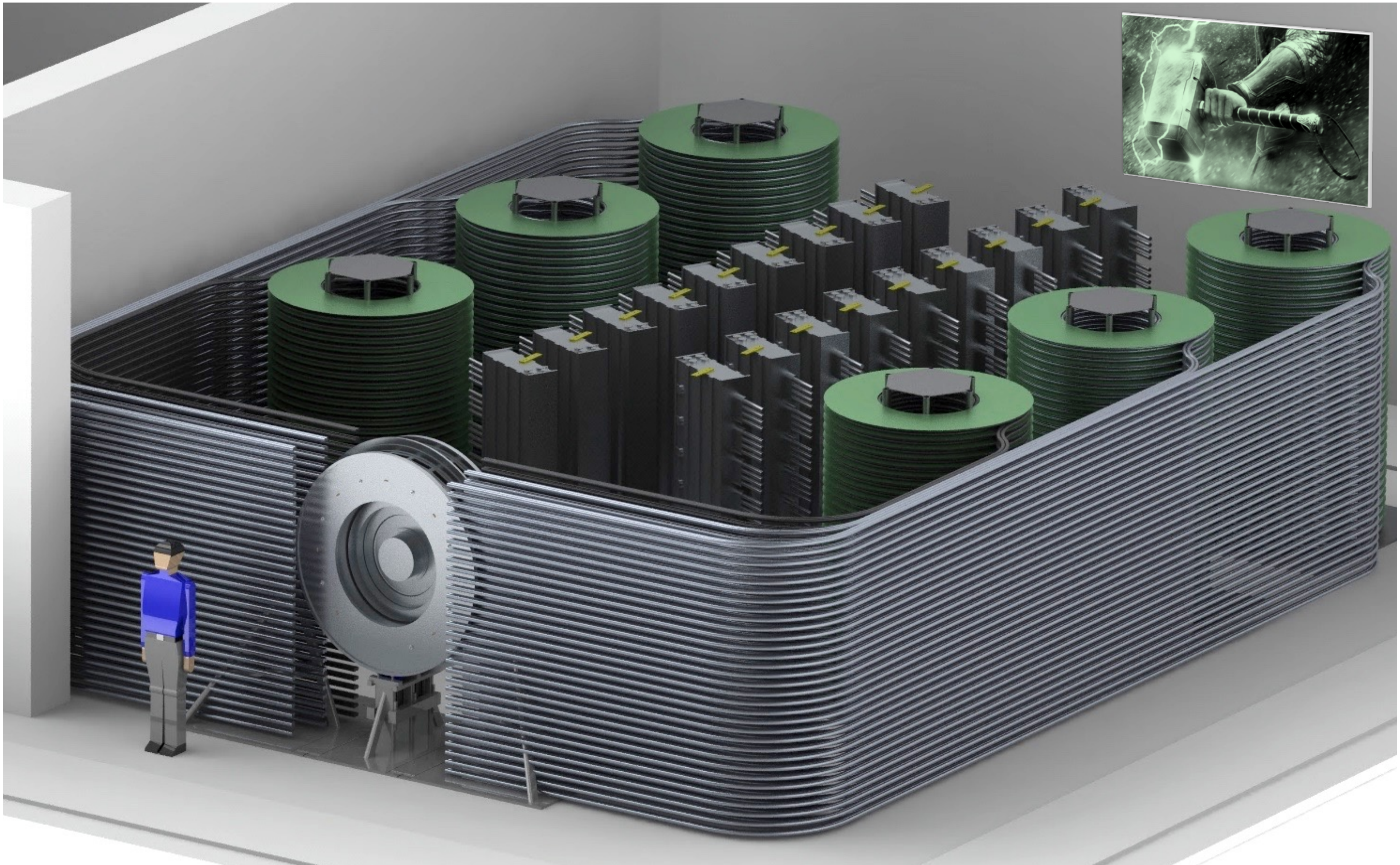
- Each of Thor’s 200 drive circuits is a single “brick”.
- Each brick consists of two 80-nF capacitors in series with a 200-kV gas switch.
- Thor stores 160 kJ and generates 1 TW of peak electrical power.
- Thor uses single-stage electrical-pulse compression and is impedance matched throughout.
- The 200 bricks are transit-time isolated from each other by 300-ns-long coaxial cables. Hence the current pulse at the load is a linear combination of 200 time-shifted pulses.
- Current loss is minimized by the use of water and solid-dielectric insulation.
- Thor does not use an explosive-driven containment system, potentially lethal energy-storage capacitors, SF_6 or any other asphyxiant or greenhouse gas, high-power lasers, or materials that include lead or other neurotoxins.

Each Thor brick stores 800 J and generates a peak electrical power of 5 GW.

A brick is a single-stage Marx generator.

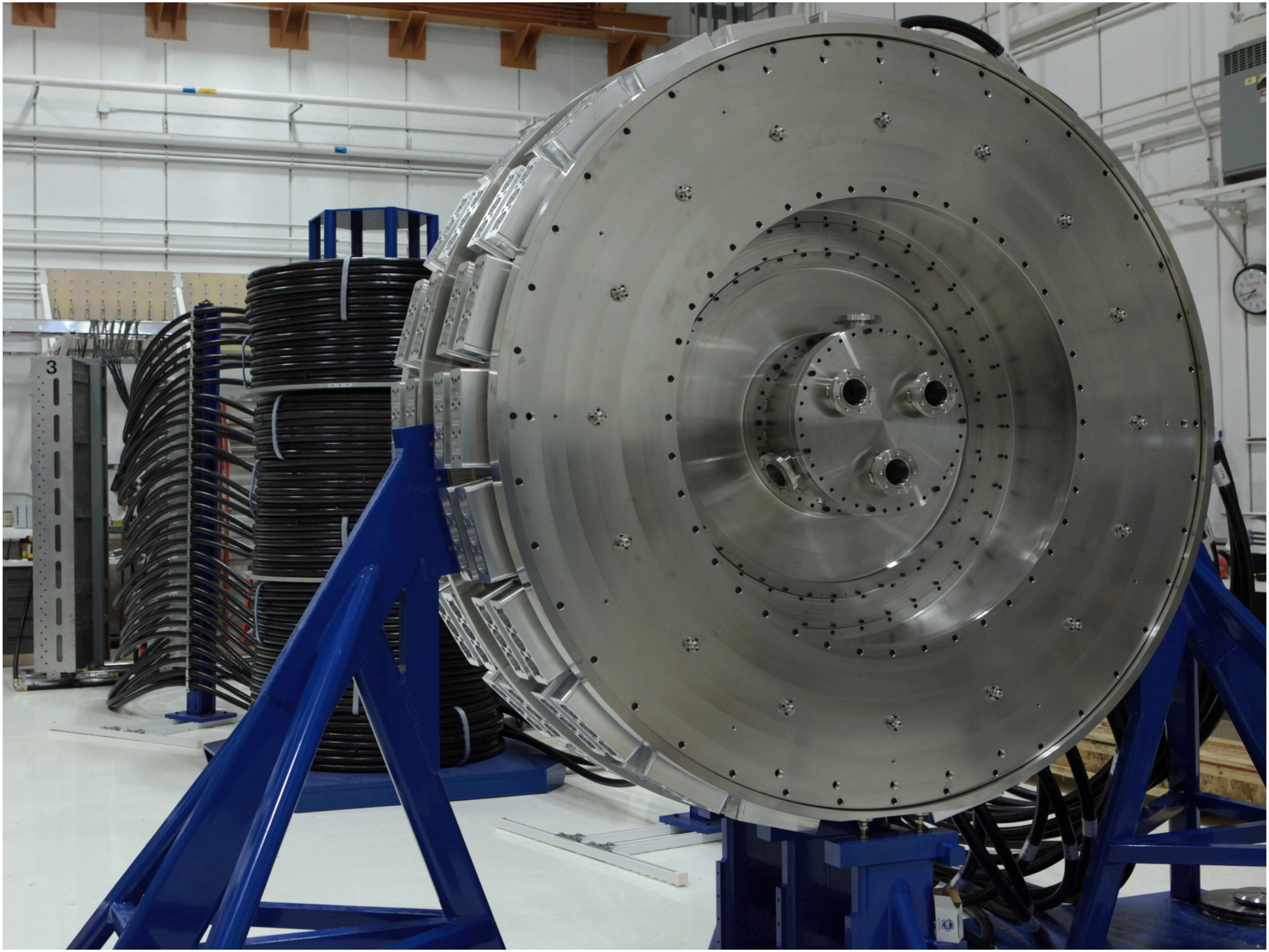
Savage (unpublished).
Woodworth et al., PRSTAB (2009).
Woodworth et al., PRSTAB (2010).
Gruner et al., IEEE PPC (2013).
Wisher, Stoltzfus, and colleagues (manuscript in preparation).





A 144-brick version of Thor is being developed at Sandia.

Reisman, Stoltzfus, Austin et al., PRSTAB **18**, 090401 (2015).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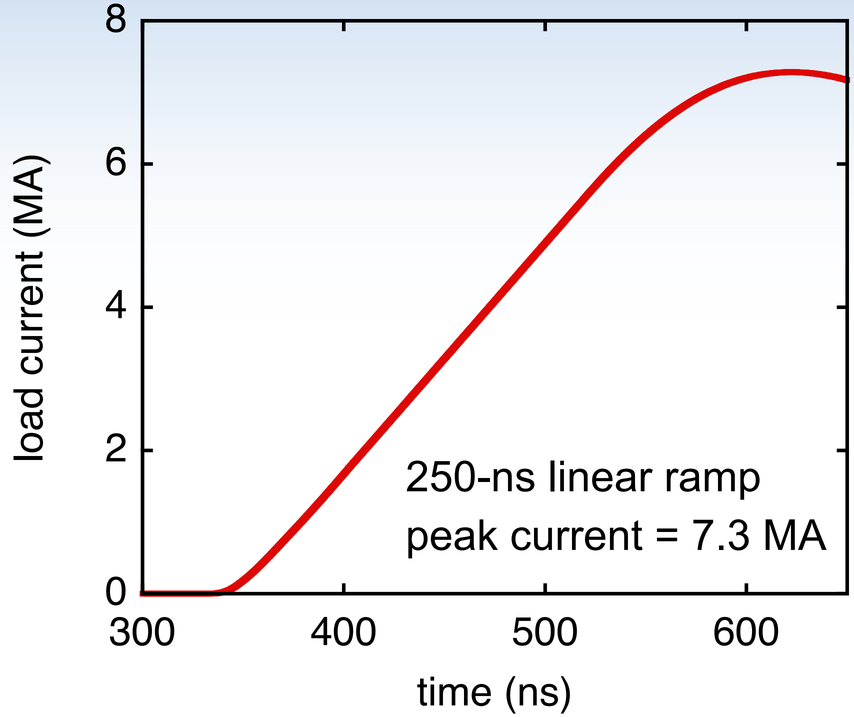
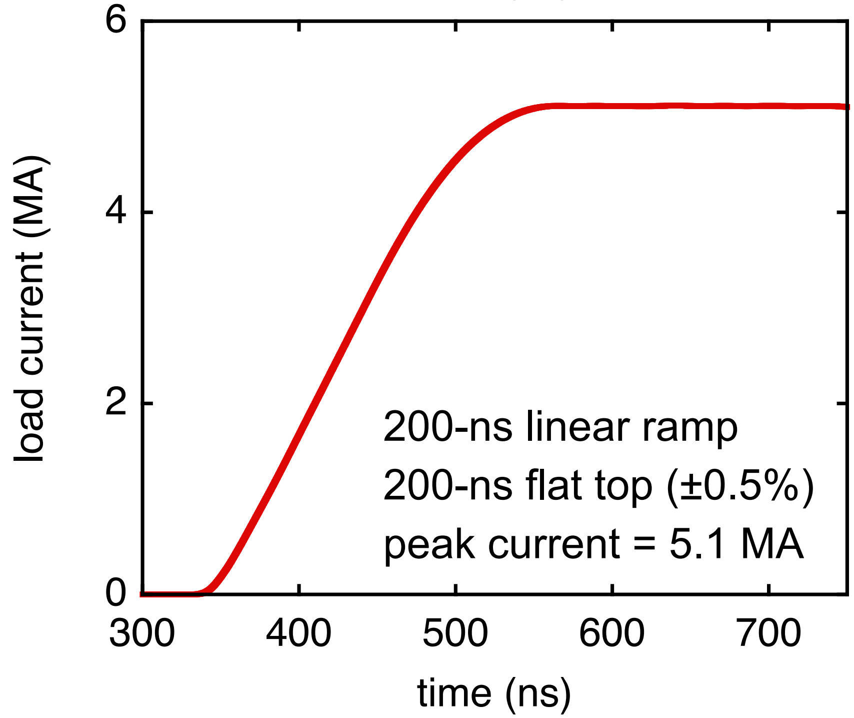
Thor can achieve a wide variety of current-pulse shapes.

Two examples are illustrated here.

- Thor can achieve a 250-ns linear ramp that peaks at 7.3 MA.
  - The magnetic pressure achieved across a 1.4-cm-wide conductor is 1.7 megabars.
- Thor can also achieve a 200-ns linear ramp followed by a 5.1-MA top that is flat to ±0.5% over 200 ns.
  - The magnetic pressure achieved across a 1.4-cm-wide conductor is 0.8 megabars.





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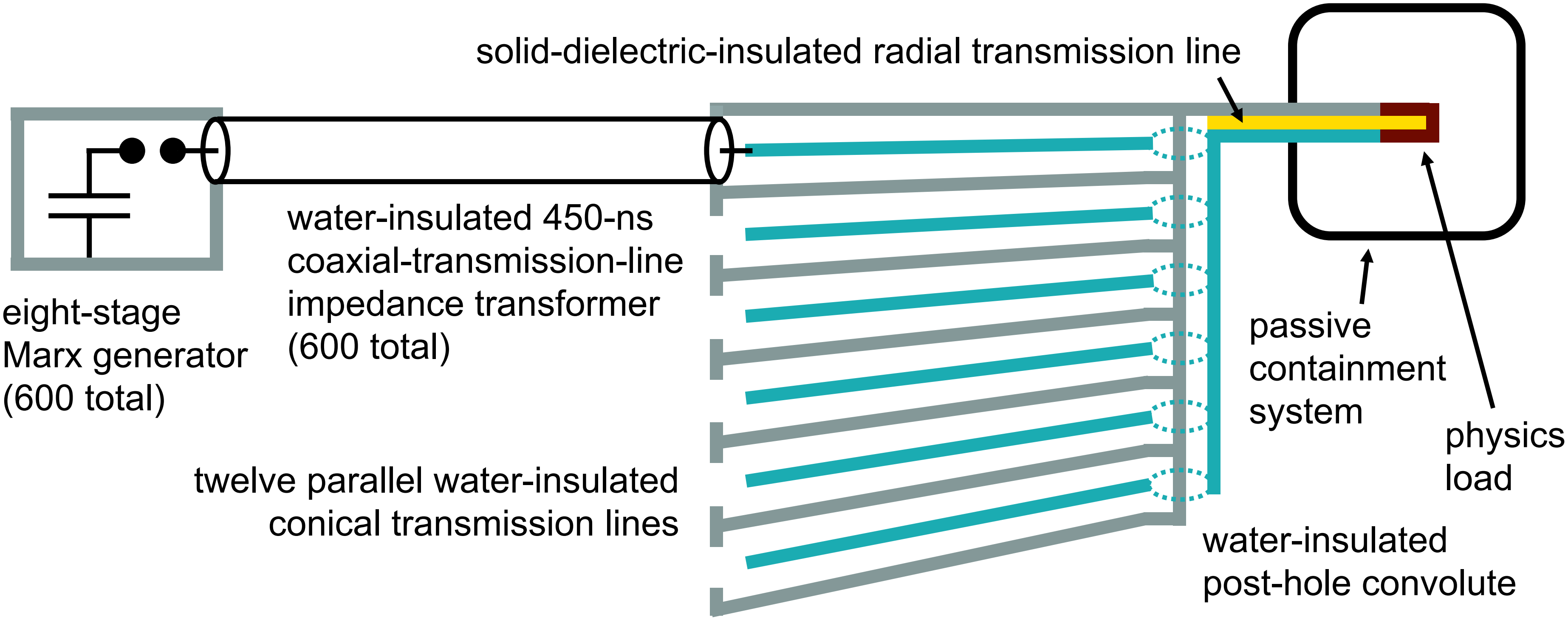
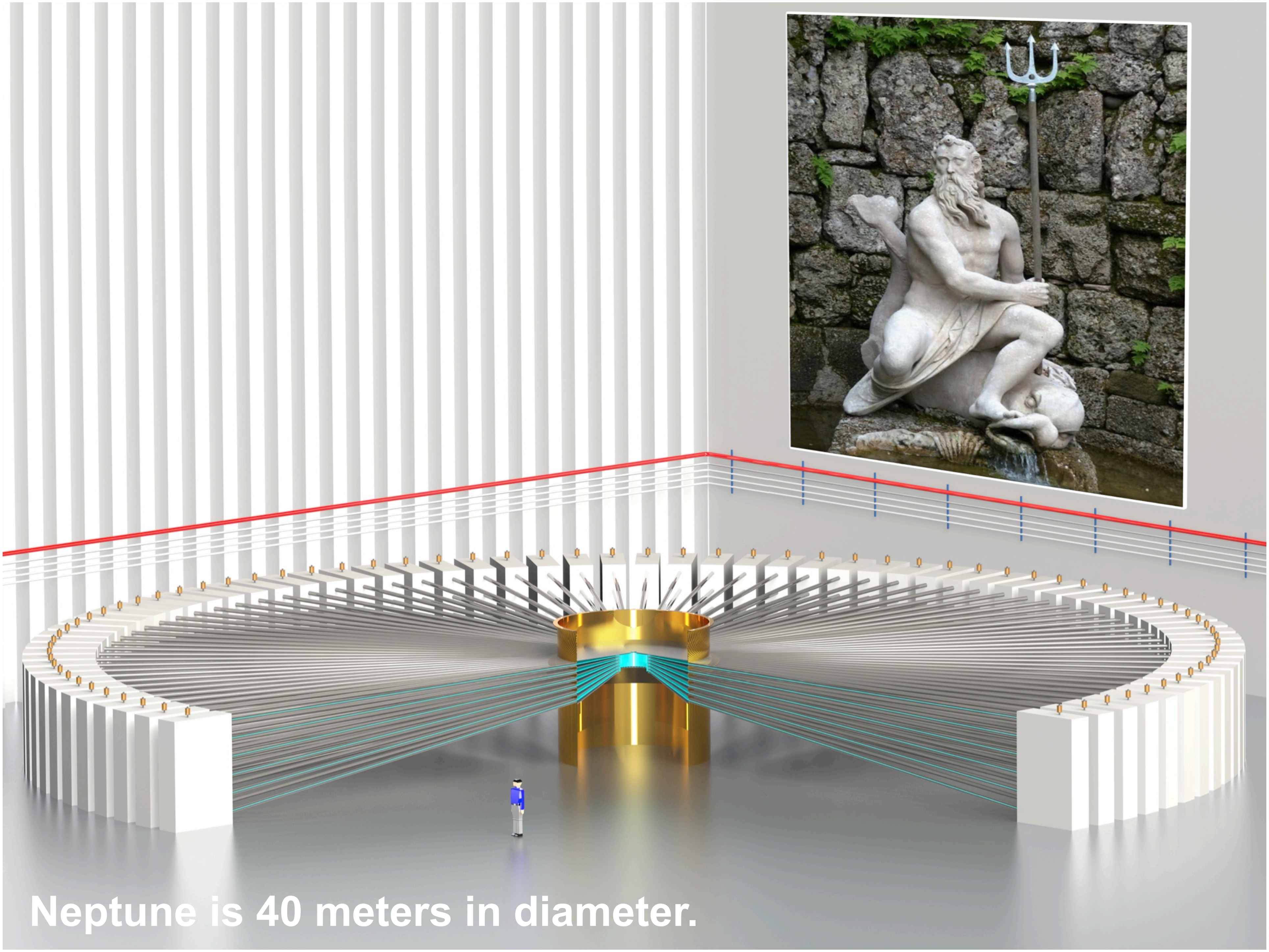
We have developed a conceptual design of Neptune.



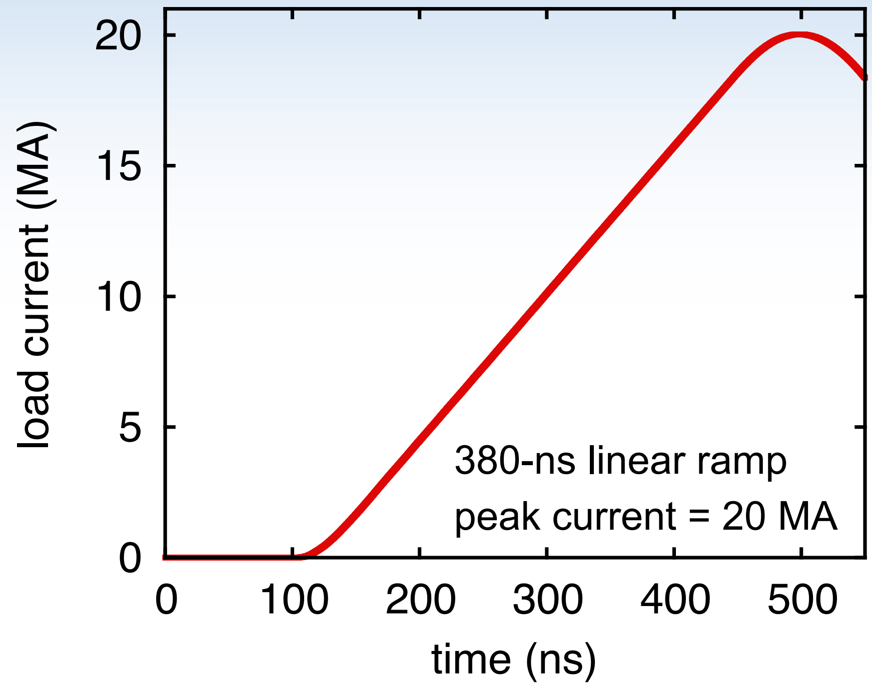
- Neptune is driven by 600 100-ns eight-stage impedance-matched Marx generators.
- Neptune stores 4.8 MJ and generates 28 TW of peak electrical power.
- Neptune uses single-stage pulse compression and is impedance matched throughout.
- The 600 Marxes are transit-time isolated from each other by 450-ns-long impedance transformers. Hence the current pulse at the load is a linear combination of 600 time-shifted pulses.
- Current loss is minimized by the use of water- and solid-dielectric insulation.
- Neptune does not use an explosive-driven containment system, potentially lethal energy-storage capacitors, SF_6 or any other asphyxiant or greenhouse gas, high-power lasers, or materials that include lead or other neurotoxins.

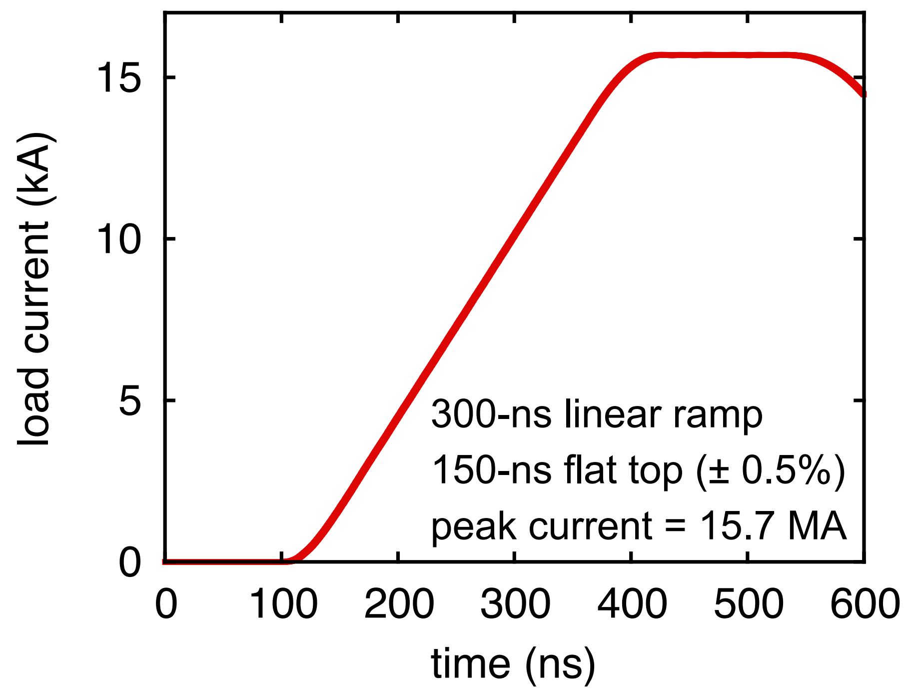

Neptune is 40 meters in diameter.

Neptune can achieve a wide variety of current-pulse shapes.

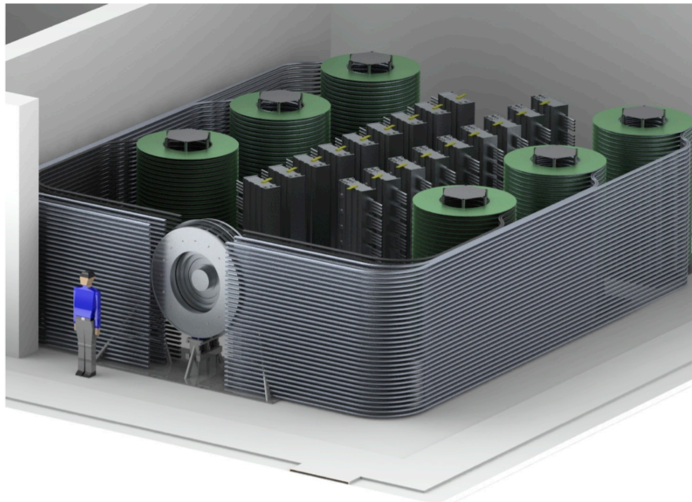
Two examples are illustrated here.

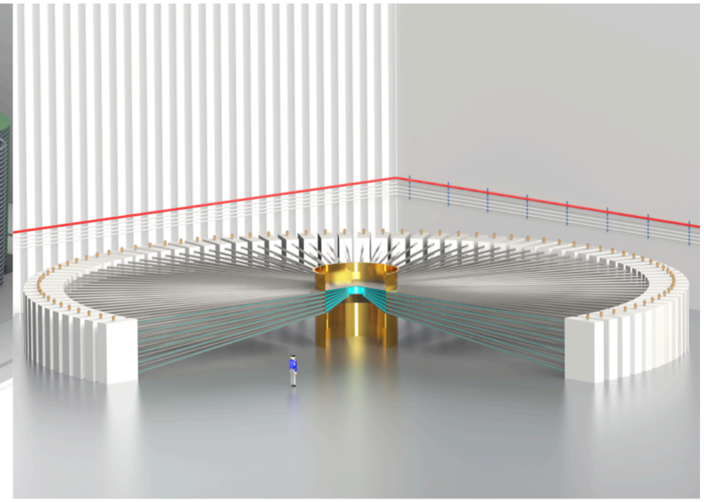
- Neptune can achieve a 380-ns linear ramp that peaks at 20 MA.
  - The magnetic pressure achieved across a 1.4-cm-wide conductor is 13 megabars.
- Neptune can also achieve a 300-ns linear ramp followed by a 15.7-MA-top that is flat to ±0.5% over 150 ns.
  - The magnetic pressure achieved across a 1.4-cm-wide conductor is 8 megabars.





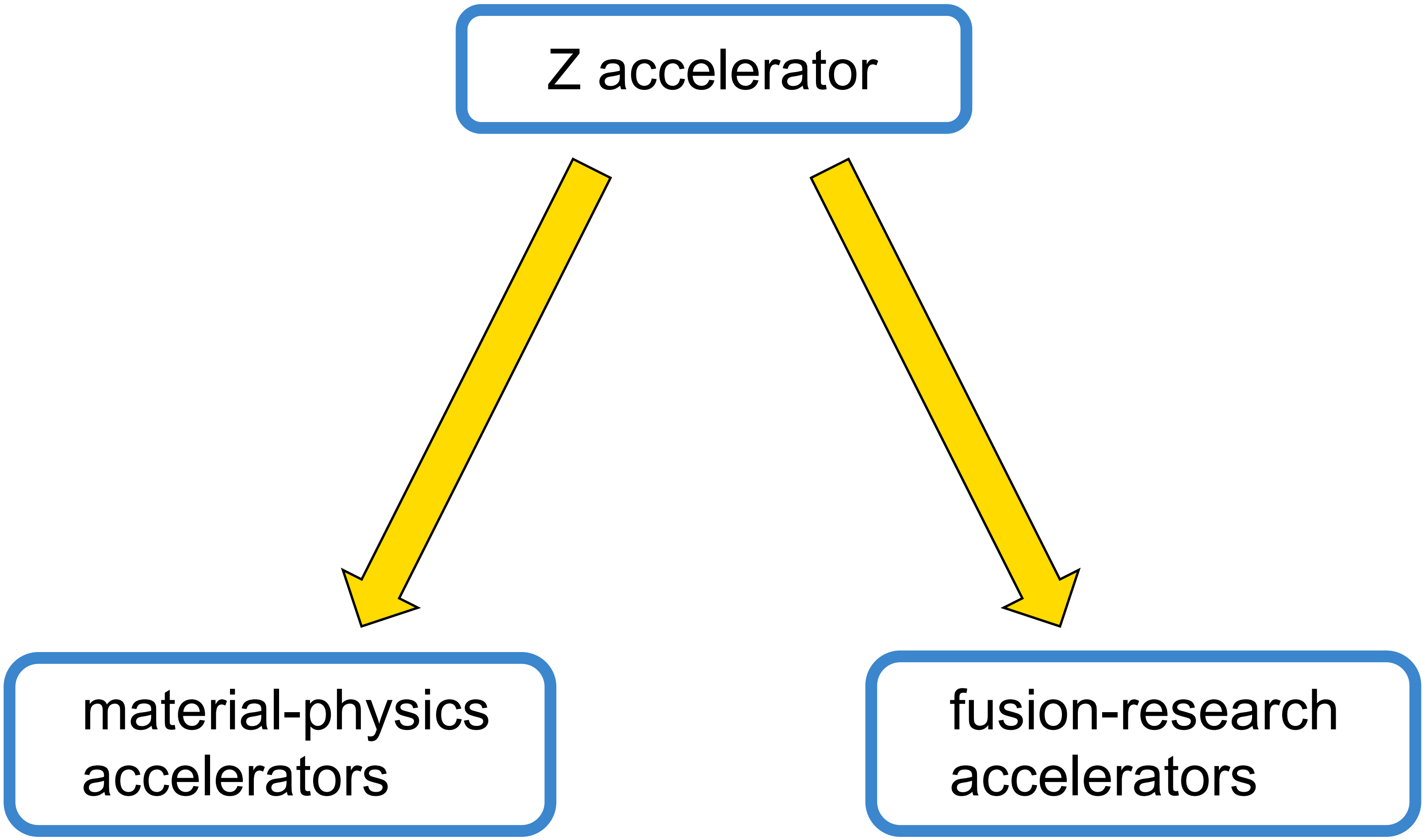
Both machines will enable interesting material-physics experiments.





parameter	Thor	Neptune
number of drive circuits	200 bricks	600 eight-brick Marxes
stored energy	160 kJ	4.8 MJ
peak electrical power	1 TW	28 TW
peak load current	7 MA (250-ns rise)	20 MA (380-ns rise)
peak magnetic pressure across a 1.4-cm-wide conductor	**1.7 megabars**	**13 megabars**

Let us now consider machines optimized for fusion research.



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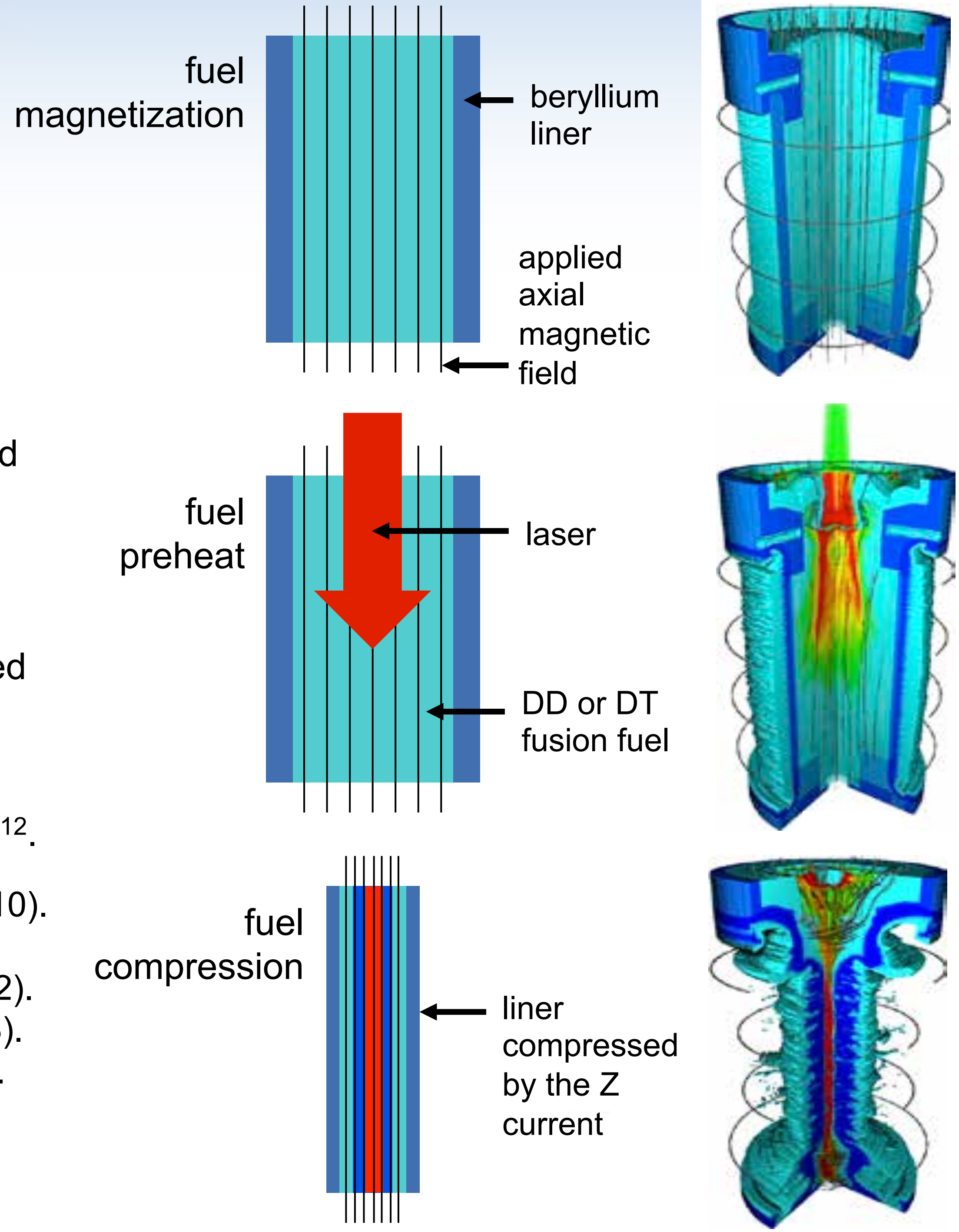
Sandia is conducting magnetized-liner interial-fusion (MagLIF) experiments on Z.

- A beryllium liner contains DD or DT fusion fuel.
- The fuel is magnetized by an applied axial magnetic field.
- The fuel is preheated by a laser.
- The fuel is subsequently compressed by the Z-accelerator current.
- To date, the MagLIF concept has achieved DD neutron yields ~3 x 10^{12}.

Slutz, Herrmann, et al., Phys. Plasmas (2010).
Slutz and Vesey, Phys. Rev. Lett. (2012).
McBride, Slutz, et al., Phys. Rev. Lett. (2012).
Awe, McBride, et al., Phys. Rev. Lett. (2013).
Sefkow, Slutz, et al., Phys. Plasmas (2014).
Gomez et al., Phys. Rev. Lett. (2014).
Schmit et al., Phys. Rev. Lett. (2014).
Slutz et al., Phys. Plasmas (2016).



We propose that next-generation accelerators be developed that are optimized for thermonuclear-fusion research.

- Pulse compression: From DC-charged capacitors to the requisite pulse in a single step.
- Impedance profile: Impedance matched throughout.
- The first such accelerator should be optimized to achieve thermonuclear ignition:
  - The fusion energy generated by this machine should exceed the electrical energy delivered by the machine to its physics load.
- The subsequent accelerator should be optimized to achieve high-yield fusion:
  - The fusion energy generated by this machine should exceed the electrical energy stored by the machine's system of capacitors.
- Accelerator simulations: The accelerator designs should enable fast and accurate circuit simulations of a shot.
- Accelerator lifetime: The accelerators should use robust long-lifetime components.
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- Proposed requirements for machines optimized for fusion experiments
- Z 300: a thermonuclear-ignition accelerator
- Z 800: a high-yield-fusion accelerator
- Linear transformer drivers (LTDs): the prime power source of Z 300 and Z 800
- Summary

Z 300 will deliver 48 MA to a MagLIF load.
The goal: thermonuclear ignition (i.e., a liner gain of ~1).

E_{LTDs} = 48 MJ

P_{LTDs} = 320 TW

diameter = 35 m

V_{stack} = 7.7 MV

L_{vacuum} = 15 nH

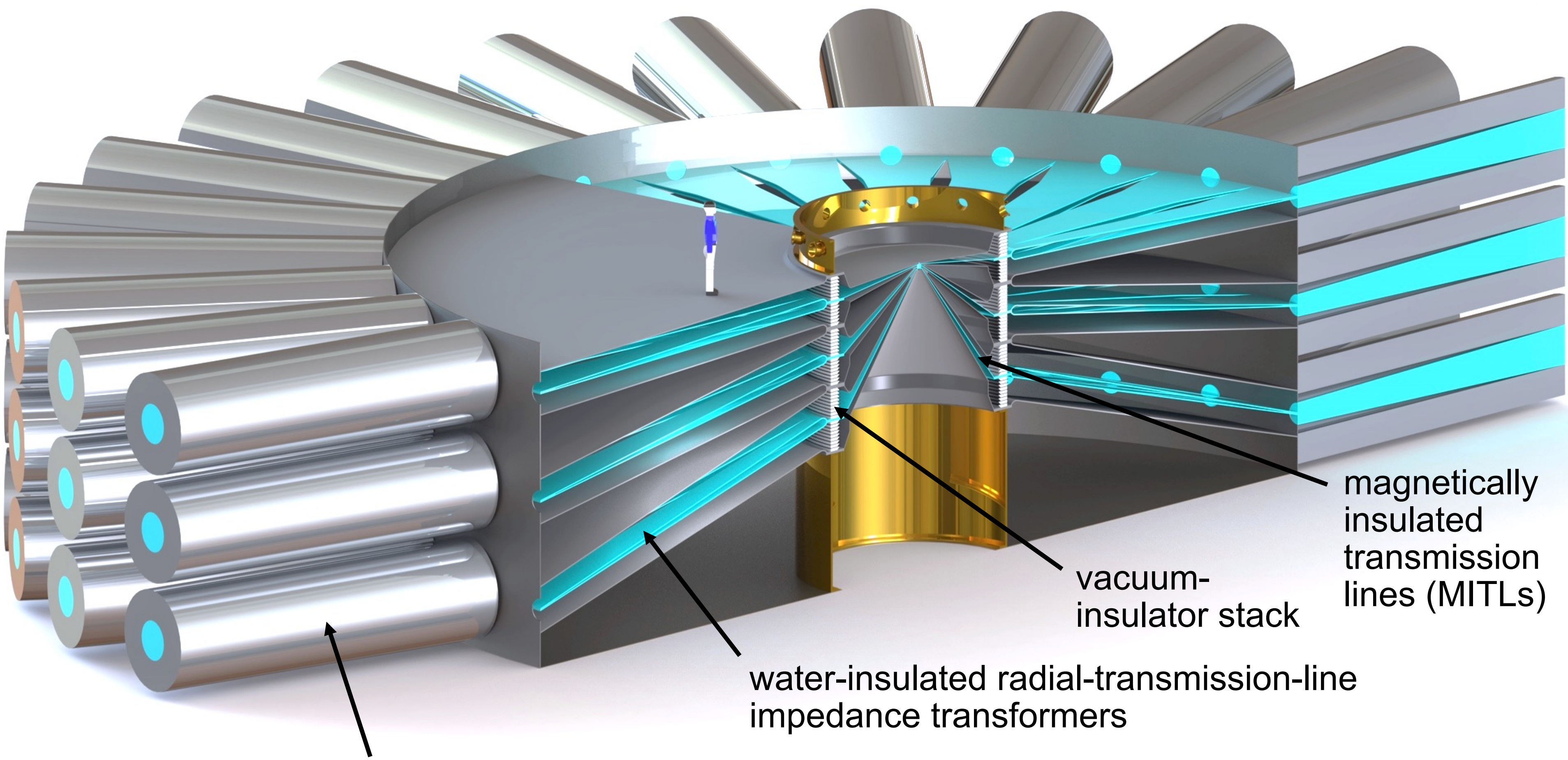
I_{load} = 48 MA

$\tau_{implosion}$ = 154 ns

P_{load} = 870 TW

E_{load} = 4.3 MJ

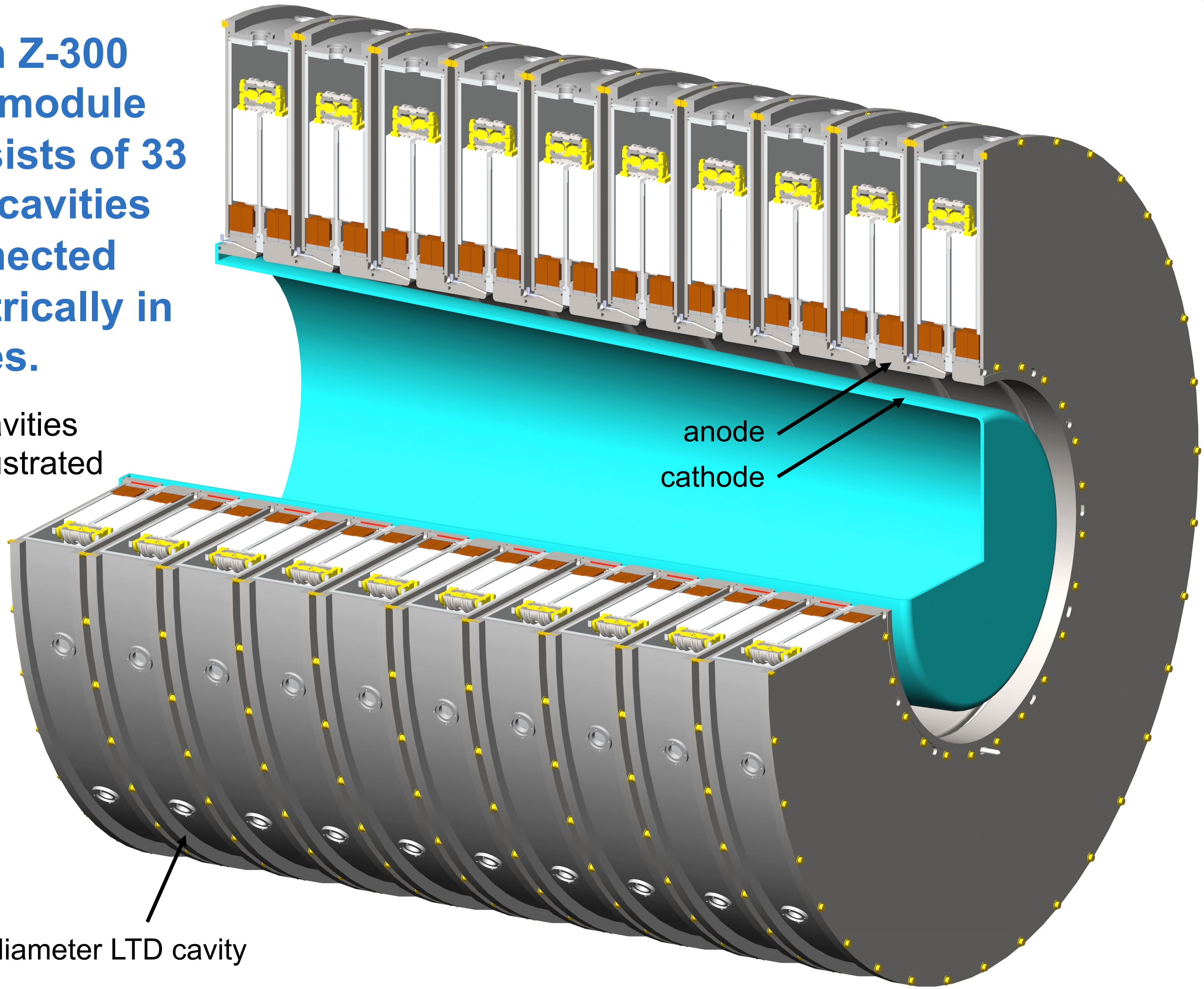
fusion yield ~ 18 MJ



Stygar et al., PRSTAB **18,** 110401 (2015).
Slutz et al., Phys. Plasmas **23**, 022702 (2016).

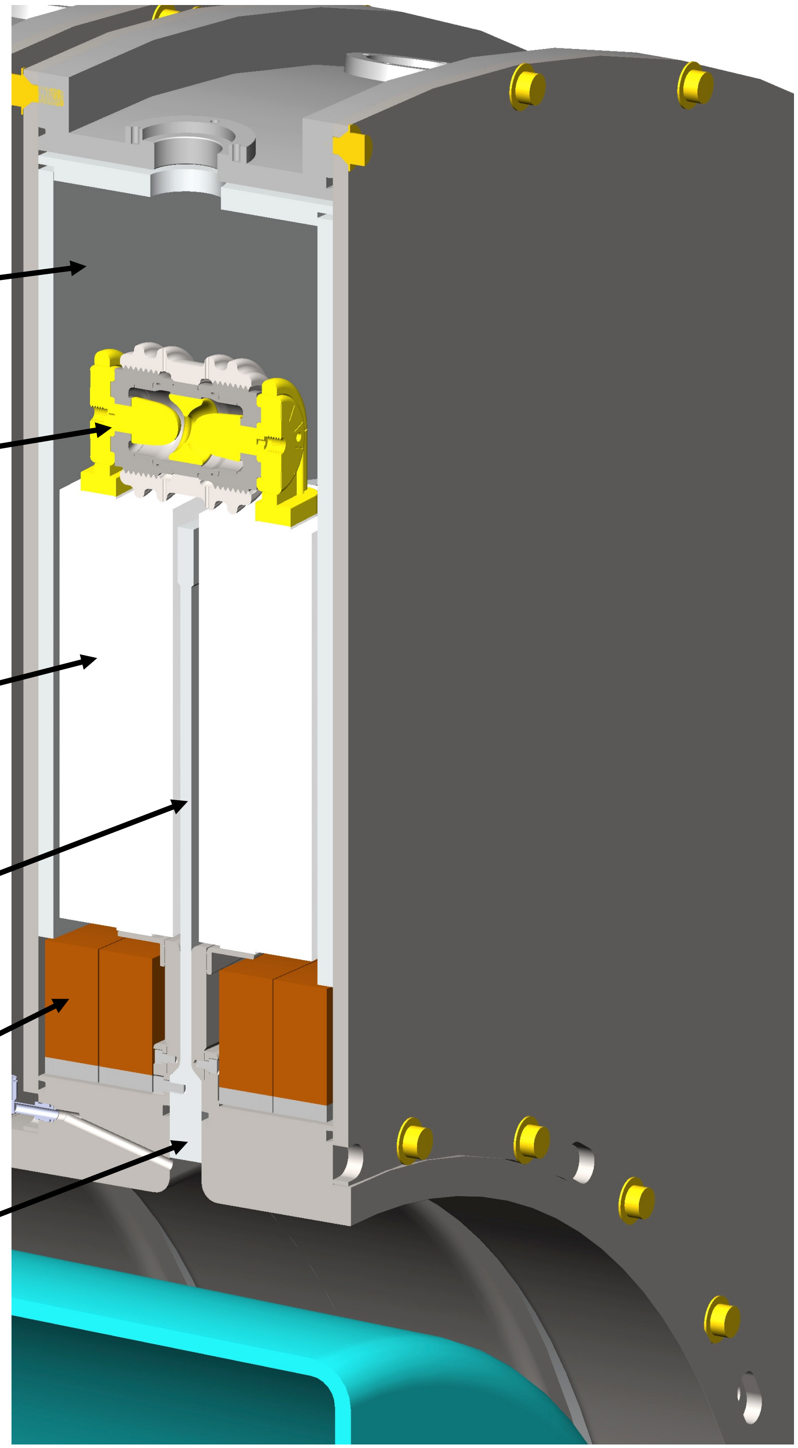
Each Z-300 LTD module consists of 33 LTD cavities connected electrically in series.

Ten cavities are illustrated here.



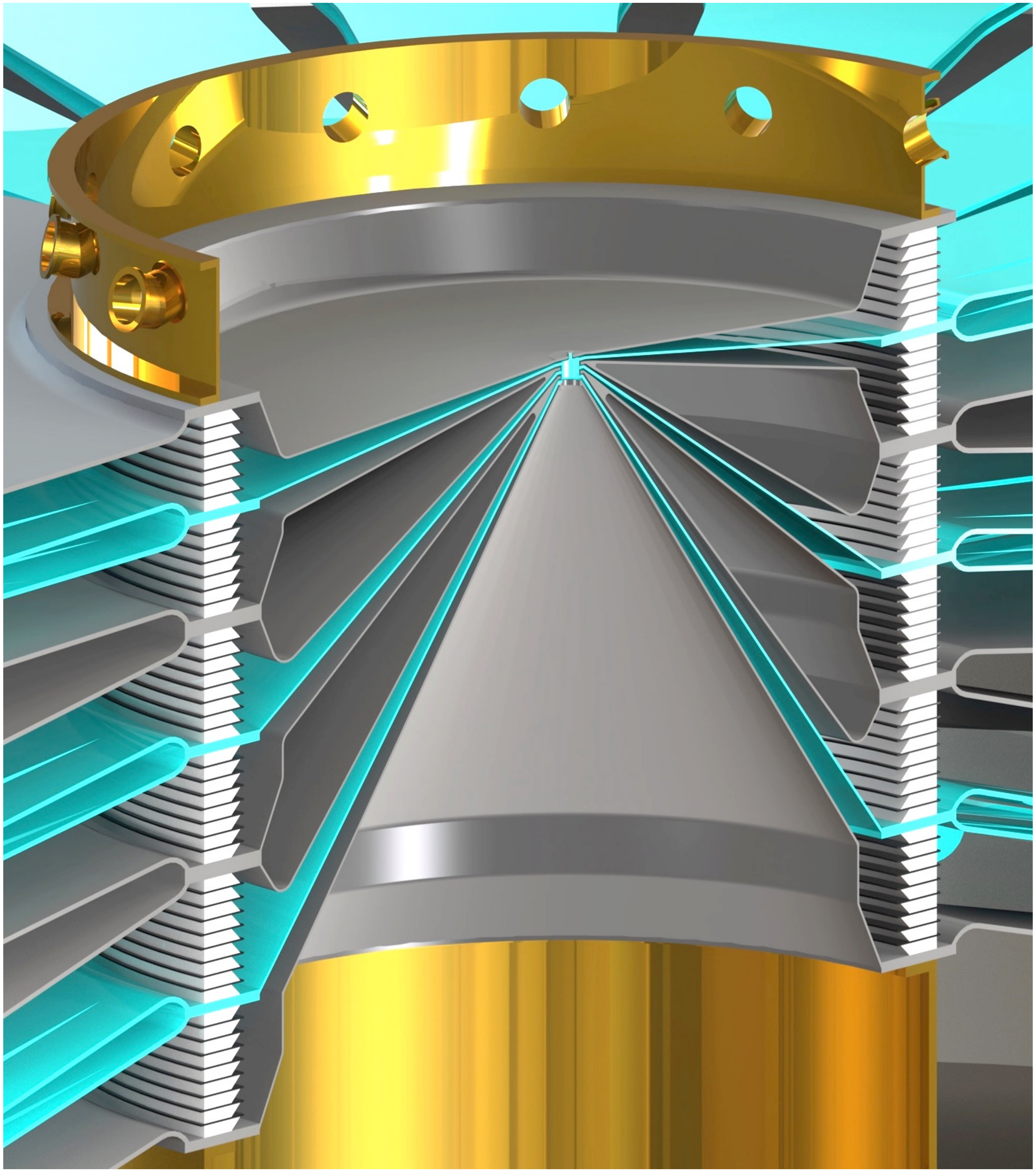
Each LTD cavity includes 20 LTD bricks connected electrically in parallel.

- Each brick consists of two 80-nF capacitors in series with a 200-kV switch.
- The capacitors are charged in a plus-minus (balanced) configuration, as suggested by Mark Savage.



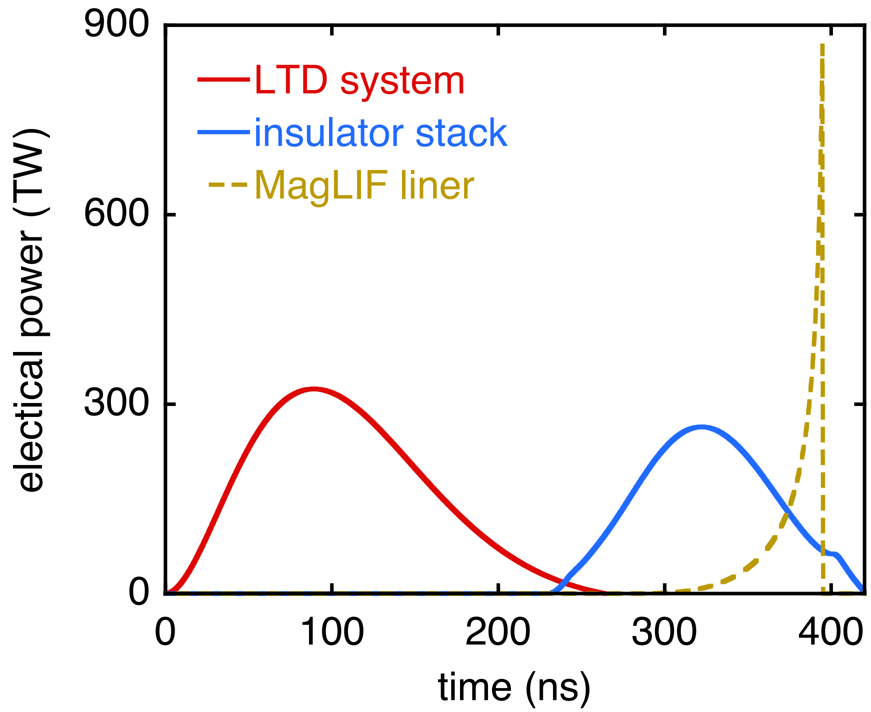
Z 300's water-insulated radial transmission-line impedance transformers drive a six-level center section.

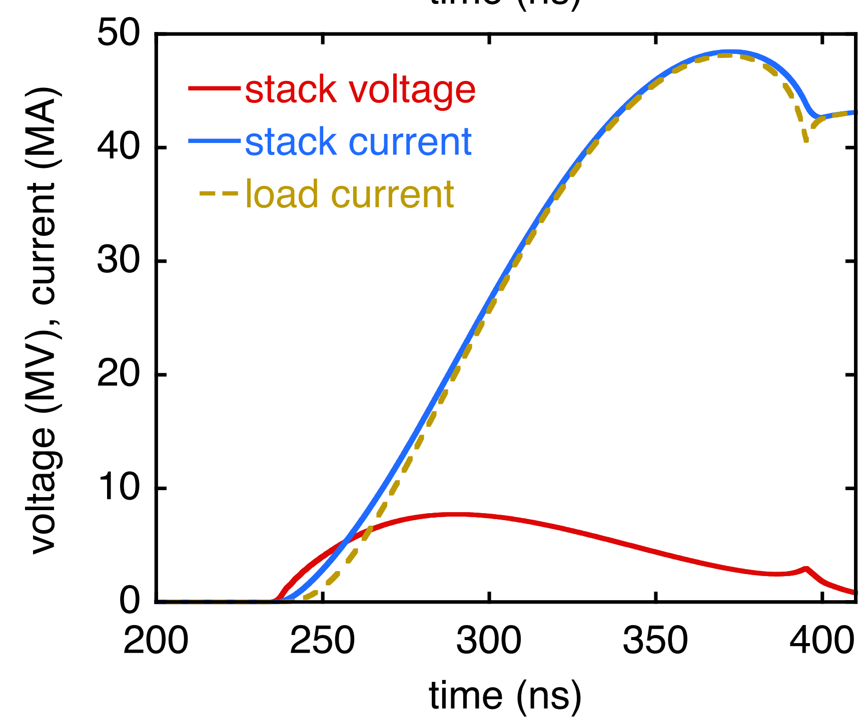
- Six 4.8-m-diameter insulator stacks serve as the water-vacuum interface.
- Six magnetically insulated transmission lines (MITLs) are connected in parallel by a triple-post-hole convolute.
- A short single MITL connects the convolute to the physics load.



Results of circuit simulations:

- Z 300's LTDs store 48 MJ, and generate a peak electrical power of 320 TW.
- The peak power at the insulator stack is 260 TW.
- The peak power delivered to an *idealized* 0D MagLIF load is 870 TW.
- The peak load current is 48 MA.
- The electrical energy delivered to the load is 4.3 MJ.
- 2D magnetohydrodynamic (MHD) simulations by Slutz and colleagues suggest the thermonuclear-fusion yield will be ~18 MJ.





Outline

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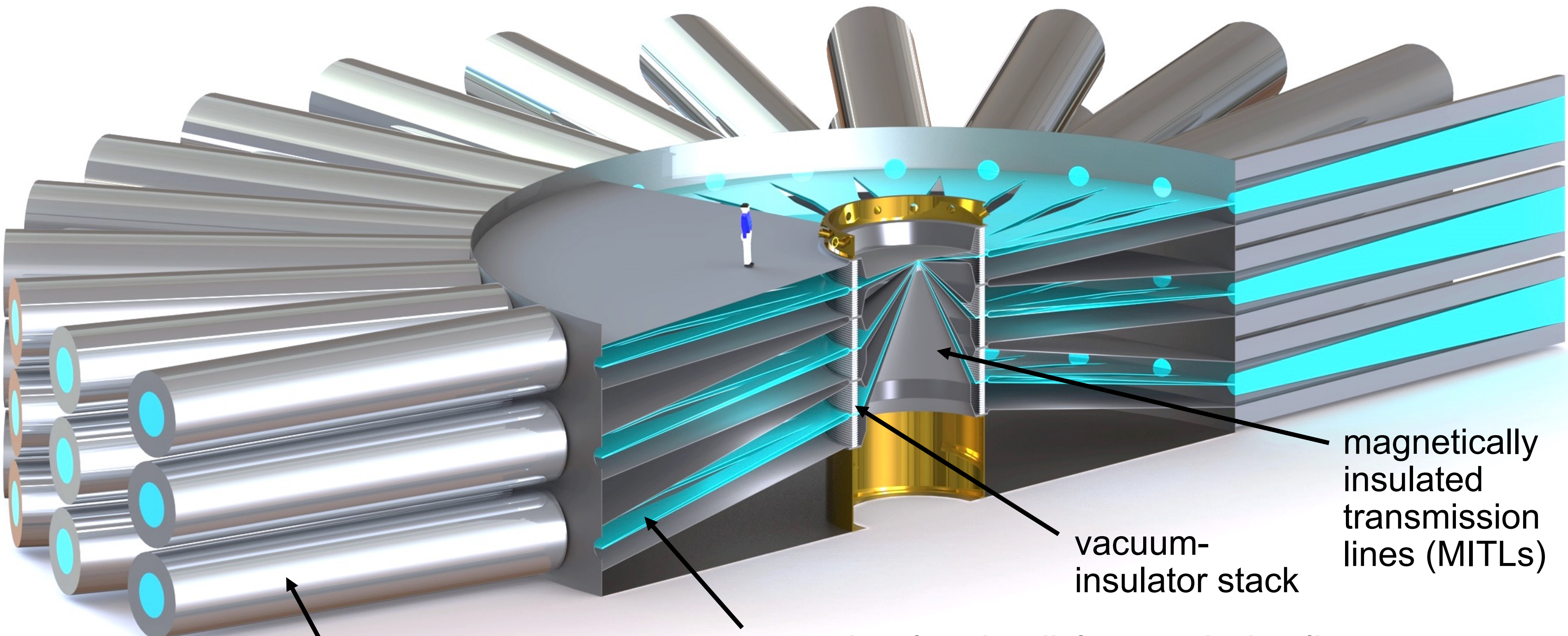
Z 800 will deliver 65 MA to a MagLIF load.
The goal: high-yield fusion (i.e., a machine gain of ~1).

E_{LTDs} = 130 MJ
P_{LTDs} = 890 TW
diameter = 52 m

V_{stack} = 15 MV
L_{vacuum} = 20 nH

I_{load} = 65 MA
$\tau_{implosion}$ = 113 ns

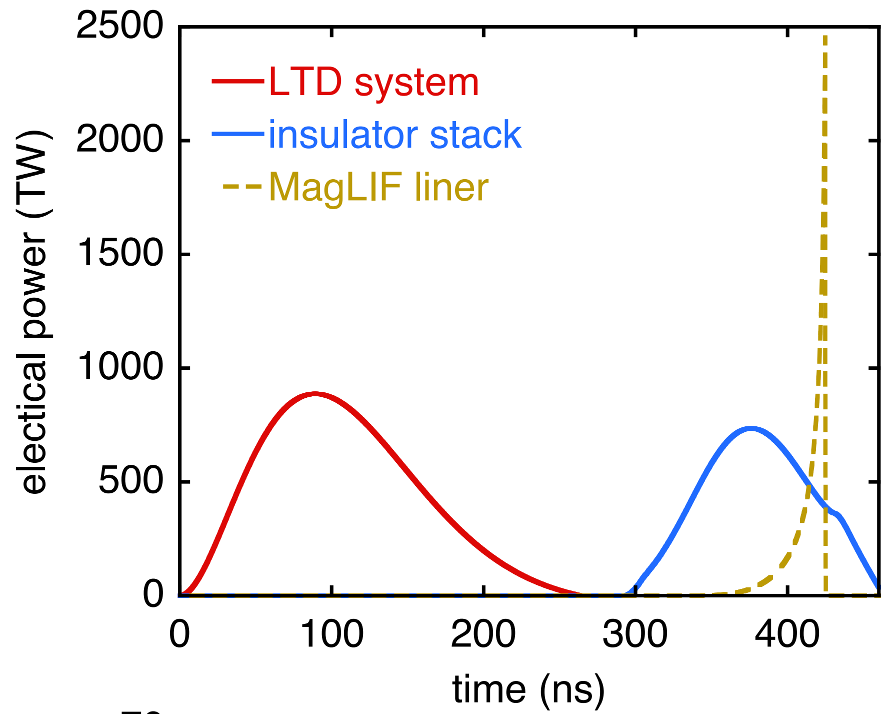
P_{load} = 2500 TW
E_{load} = 8.0 MJ
fusion yield ~ 440 MJ

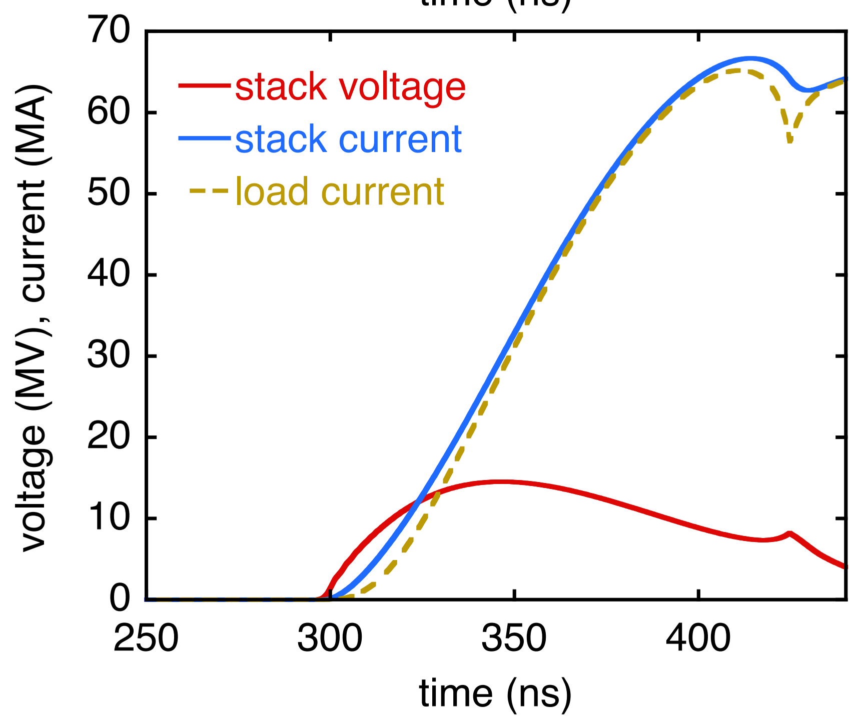


Stygar et al., PRSTAB **18,** 110401 (2015).
Slutz et al., Phys. Plasmas **23**, 022702 (2016).

Results of circuit simulations:

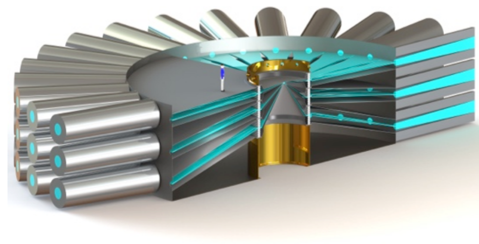
- Z-800's LTDs store 130 MJ, and generate a peak electrical power of 890 TW.
- The peak power at the insulator stack is 740 TW.
- The peak power delivered to an *idealized* 0D MagLIF load is 2500 TW.
- The peak load current is 65 MA.
- The electrical energy delivered to the load is 8.0 MJ.
- 2D magnetohydrodynamic (MHD) simulations by Slutz and colleagues suggest the thermonuclear-fusion yield will be ~440 MJ.

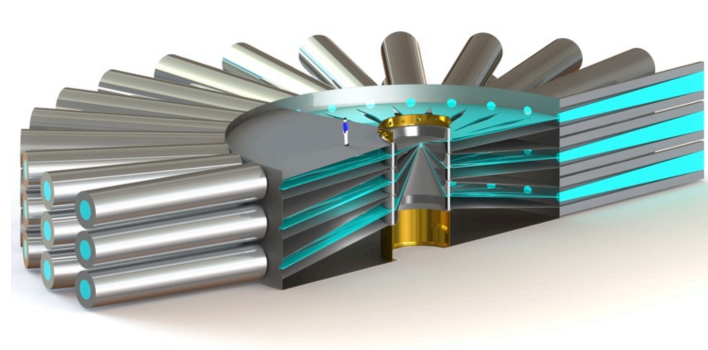




Both machines will enable interesting fusion experiments.

Slutz et al., Phys. Plasmas (2016).
Stygar et al., PRSTAB (2015).





parameter	Z 300	Z 800
accelerator diameter	35 m	52 m
stored energy	48 MJ	130 MJ
peak electrical power	320 TW	890 TW
peak load current	48 MA	65 MA
implosion time	150 ns	113 ns
power delivered to the liner	870 TW	2500 TW
energy delivered to the liner	4.3 MJ	8.0 MJ
DT-fusion yield [2D MHD simulations: Slutz et al., Phys. Plasmas (2016)]	**~18 MJ**	**~440 MJ**

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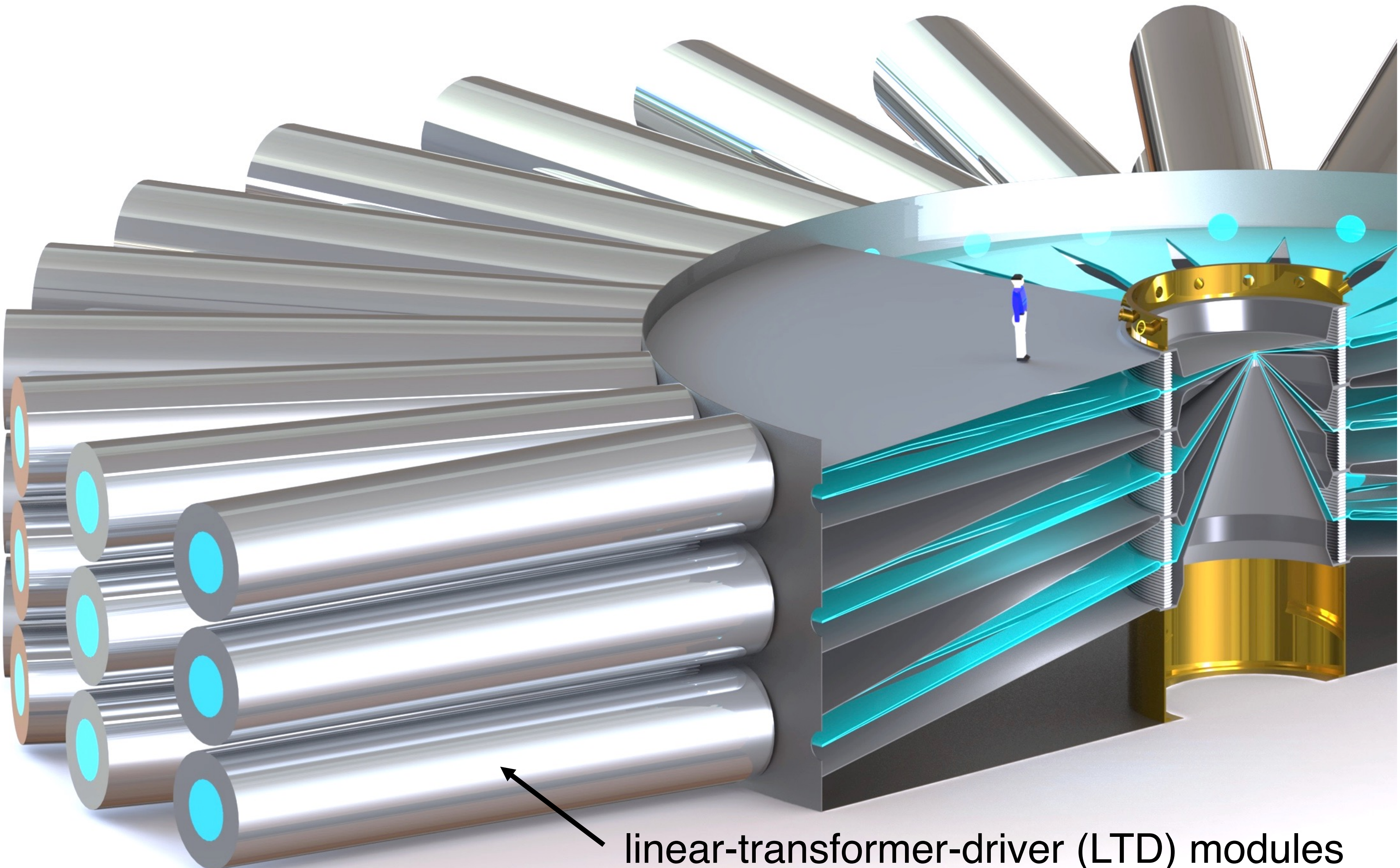
Both Z 300 and Z 800 are driven by linear-transformer-driver (LTD) modules.



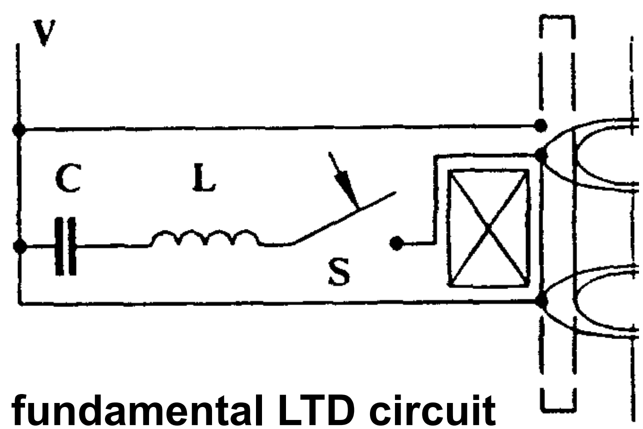
The linear-transformer-driver (LTD) concept was pioneered by Koval'chuk, Vizir, Kim, and colleagues.

- The concept was developed at the High Current Electronics Institute (HCEI), Tomsk, Russia.
- The original concept generated a current pulse with a 1 μs rise time, and was intended to be used with a plasma opening switch to shorten the pulse.
- Since then, the concept has been advanced further by HCEI, and in addition, Hutsel, LeChien, Leckbee, Long, Mazarakis, McDaniel, Savage, Spielman, Stoltzfus, Wisher, and co-workers (Sandia National Labs), Rose and Welch (Voss Scientific), and many others worldwide.
- LTDs now generate rise times ~ 100 ns, so an opening switch is no longer needed.

Russian Physics Journal, Vol. 40, No. 12, 1997

FAST PRIMARY STORAGE DEVICE UTILIZING A LINEAR PULSE TRANSFORMER

B. M. Koval'chuk, V. A. Vizir', A. A. Kim, E. V. Kumpyak, S. V. Loginov, A. N. Bastrikov, V. V. Chervyakov, N. V. Tsoi, P. Monjaux, and D. Kh'yui



fundamental LTD circuit

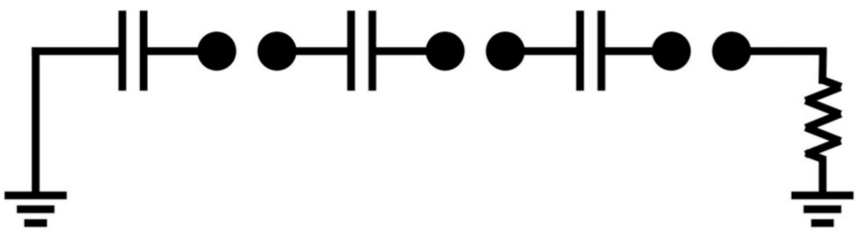
A description is given of sections of a linear pulse transformer (a linear transformer driver, LTD) intended for use as a fast primary storage device in pulse generators with intermediate inductive energy storage. The results of tests of LTDs consisting of 3 and 10 series-connected sections are given. Results are described for experiments on coupling energy out of such a generator using a plasma opening switch.

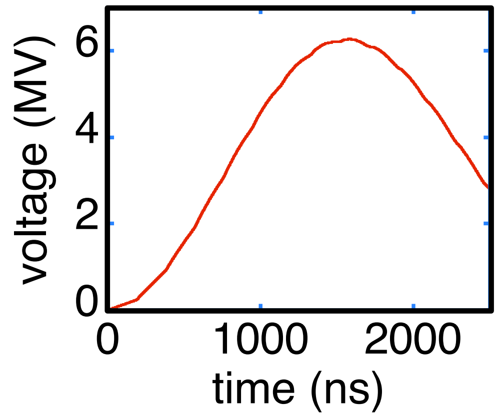
LTDs are the greatest advance in prime-power generation since the invention of the Marx generator in 1924.

A Marx generator and an LTD both charge capacitors in parallel and discharge them in series. A Marx does this as an *LC circuit*:

Z Marx generator:

$2\sqrt{LC} = 1500$ ns

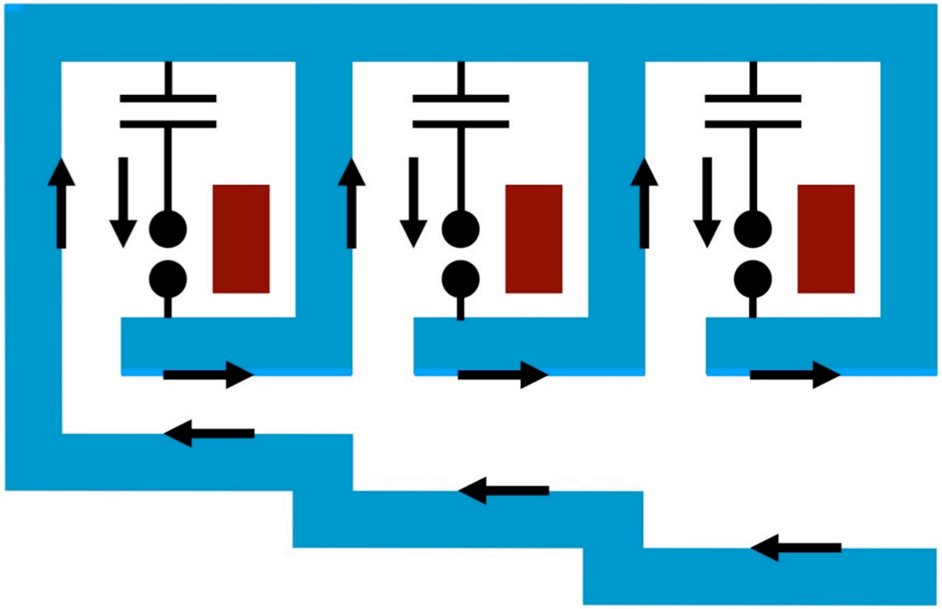


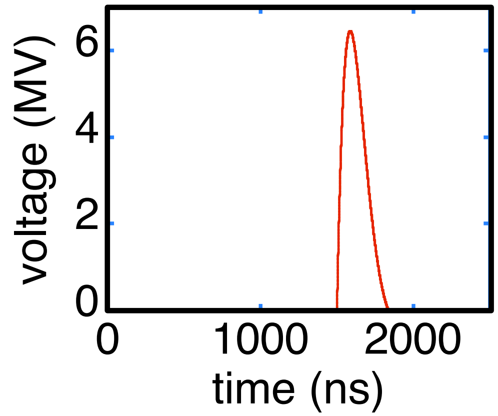


An LTD does this as an *induction voltage adder*, in which each of the adder's cavities is driven by LC circuits *contained within the cavity*:

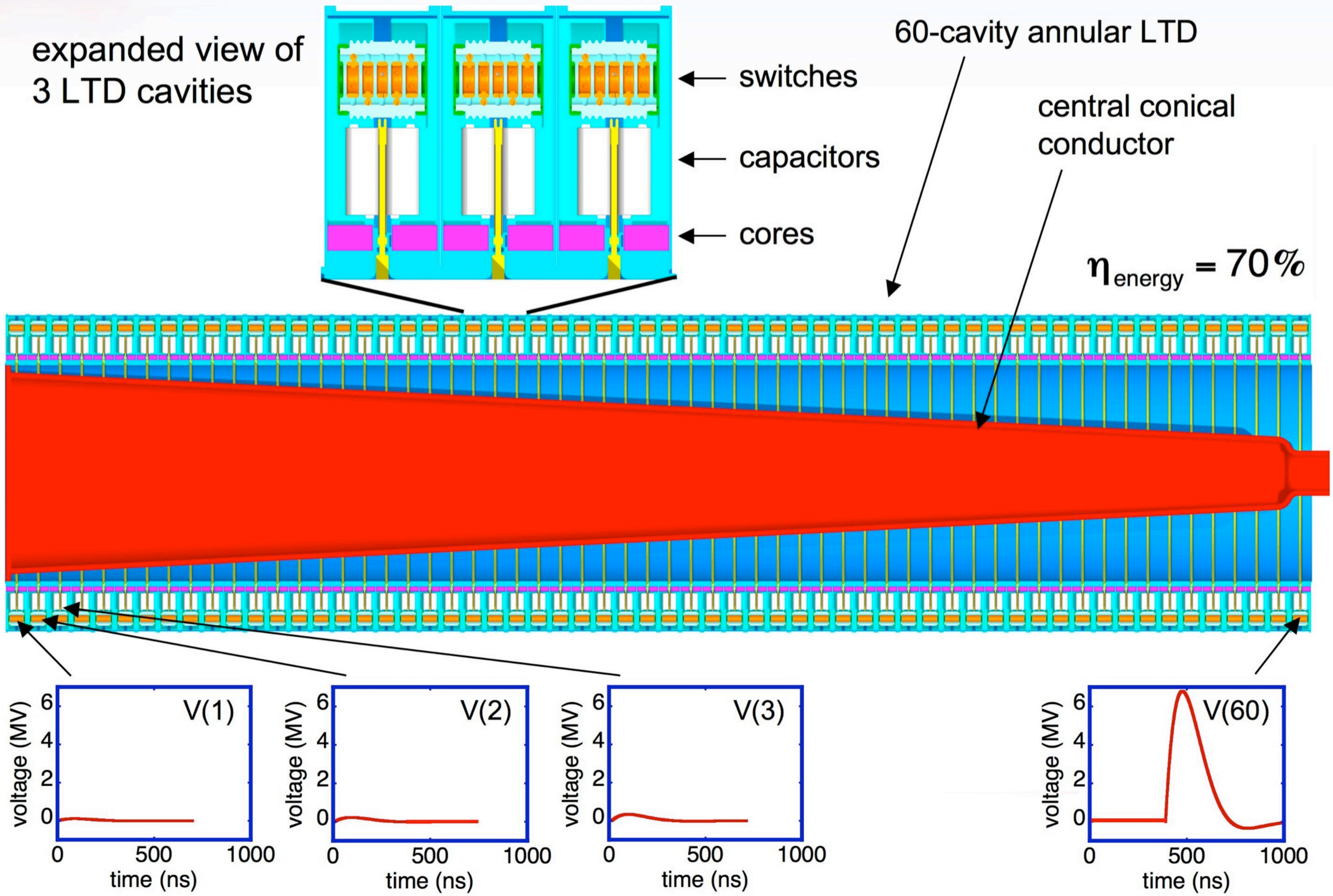
LTD module:

$2\sqrt{LC} = 160$ ns





An LTD module is an electromagnetic analogue to a laser: Power amplification is achieved by *triggered* emission of radiation.

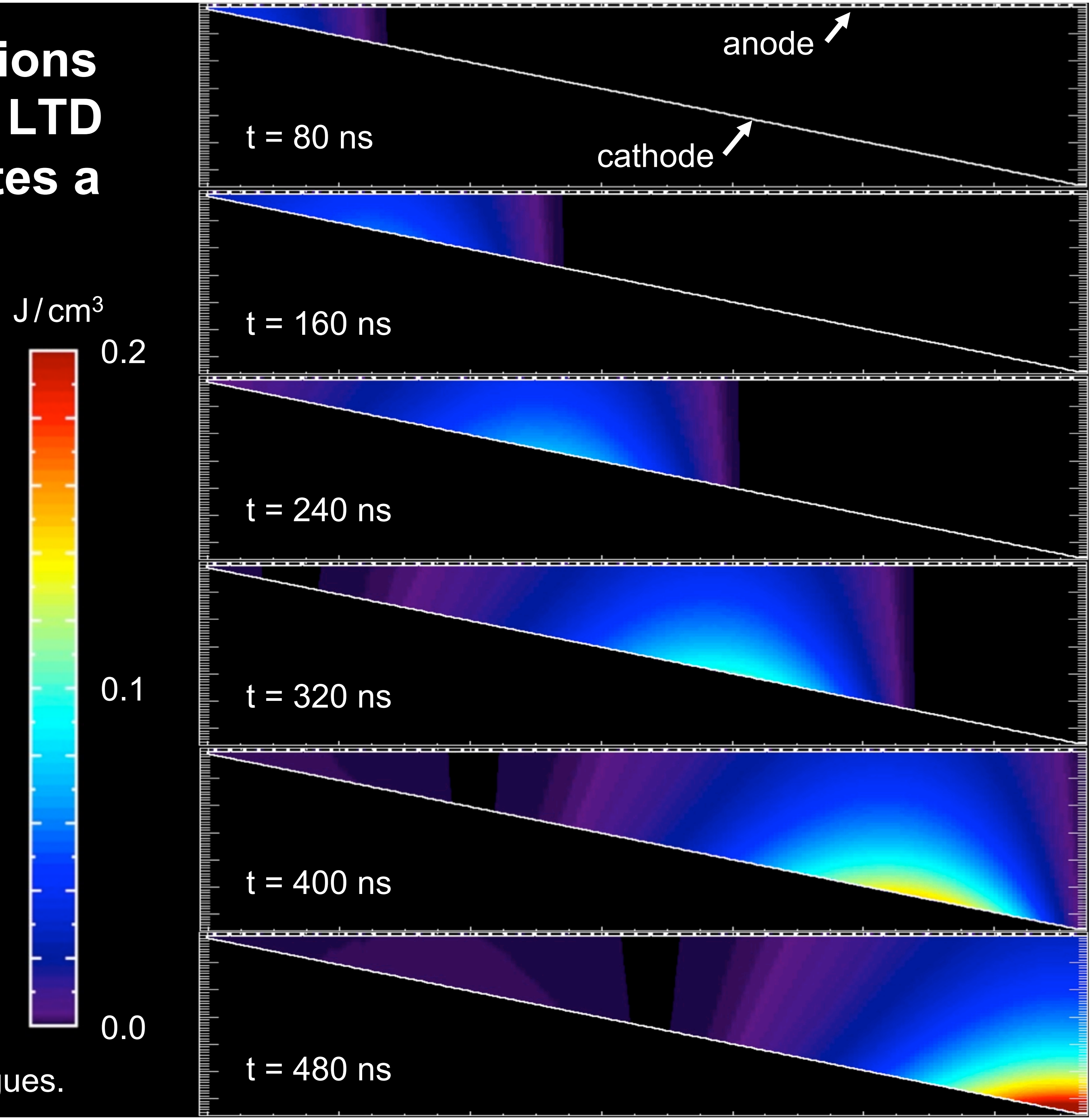


2D LSP simulations confirm that an LTD module generates a clean electrical power pulse.

Calculations agree to within 2%:

- Analytic model: 6.49 TW.
- 1D circuit: 6.49 TW.
- 2D LSP simulation: 6.38 TW.

The simulations illustrate power amplification.



Welch, Rose, and colleagues.

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Summary

- We propose to apply a new architecture to the designs of next-generation pulsed-power accelerators.
- The architecture is based on two concepts: single-stage electrical-pulse compression and impedance matching.
- We have applied the architecture to conceptual designs of two machines optimized for material-physics research: Thor and Neptune.
  - Thor will deliver as much as 7 MA to a load, and achieve magnetic pressures as high as 1.7 megabars (across a 1.4-cm-wide planar conductor).
  - Neptune will deliver as much as 20 MA to a load, and achieve magnetic pressures as high as 13 megabars (across a 1.4-cm-wide planar conductor).
- We have also applied the architecture to conceptual designs of two machines optimized for thermonuclear-fusion experiments: Z 300 and Z 800.
  - Z 300 will deliver 48 MA to a MagLIF load. The goal of Z 300 is to achieve thermonuclear ignition; i.e., a liner gain of ~1.
  - Z 800 will deliver 65 MA to a load. The goal of Z 800 is to achieve high-yield thermonuclear fusion; i.e., a machine gain of ~1.
- You are invited to work with us to develop these four next-generation accelerators.